Universals in complex, robust networks

Today's focus on fundamentals

- Concepts: Complexity, robustness, and fragility
- Theory: Fundamental laws, constraints, tradeoffs
- Network architecture
- Illustrate with "simple" and familiar case studies

- Warm up with some (hopefully familiar) examples

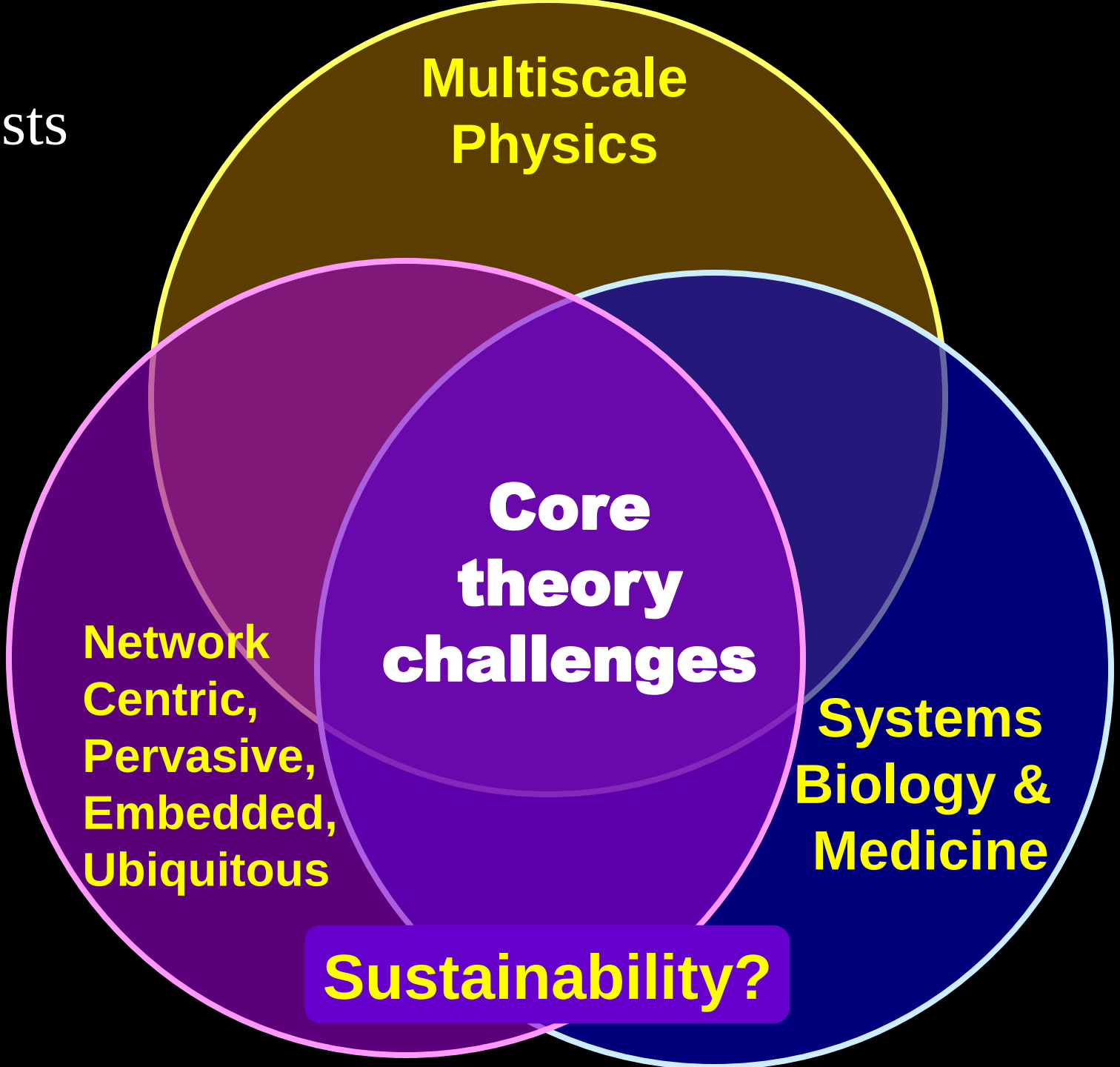
John Doyle

John G Braun Professor

Control and Dynamical System, Electrical Engineering, BioEngineering

Caltech

My interests



“Architecture”

- Most persistent, ubiquitous, and global features of organization
- Constrains what is possible for good or bad
- Platform that enables (or prevents) innovation, sustainability, etc,
- Existing architectures are unsustainable
- Internet, biology, energy, manufacturing, transportation, water, food, waste, law, etc
- Theoretical foundation is fragmented, incoherent, incomplete

Infrastructure networks?

- Power
- Transportation
- Water
- Waste
- Food
- Healthcare
- Finance

All examples of "bad" architectures:
- Unsustainable
- Hard to fix

Where do we look for "good" examples?

Informative case studies in architecture

- Internet and related technology (OS)
- Systems biology (particularly, bacterial biosphere)
- System medicine and physiology
- Ecosystems (e.g. So Cal wildfire ecology)
- Aerospace systems
- Electronic Design Autom. (Platform Based Design)

- Multiscale physics (turbulence, stat mech)
- Misc: buildings/cities, Lego, clothing/fashion, barter/markets/money/finance, social/political

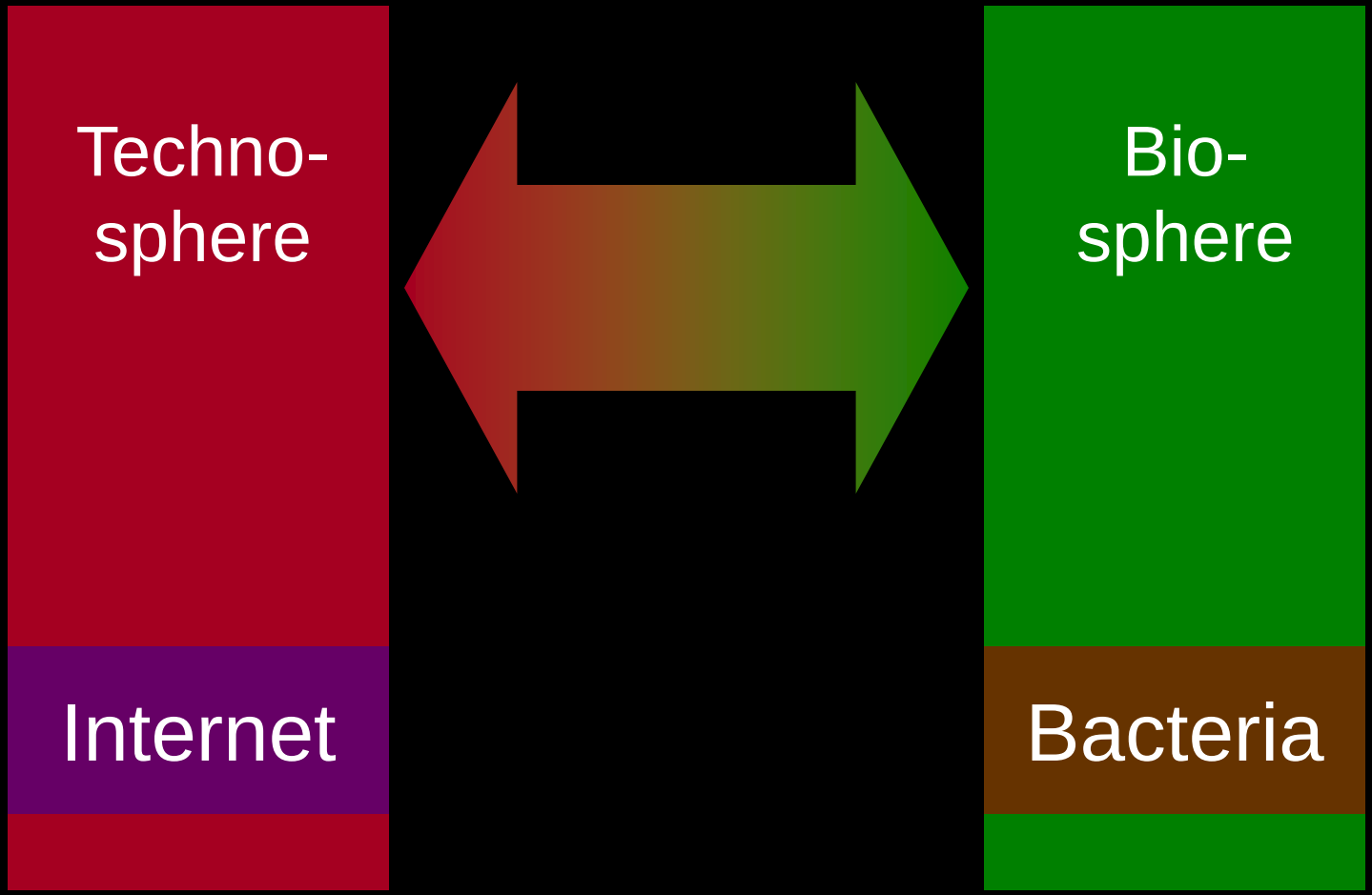
- Successful architectures
- Robust, evolvable
- Universal, foundational
- Accessible, familiar
- Unresolved challenges
- New theoretical frameworks
- Boringly retro?

Simplest case studies

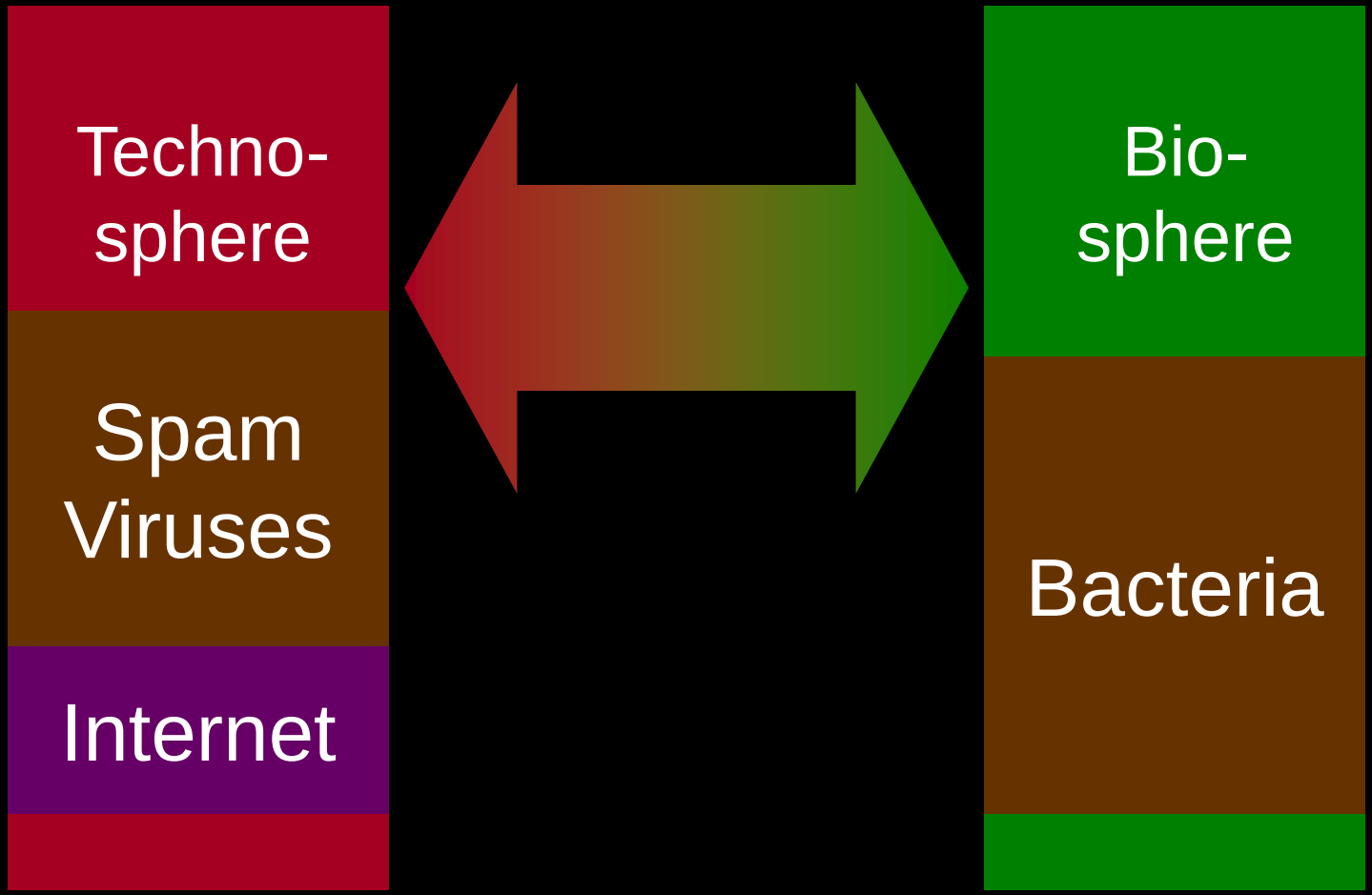
Internet

Bacteria

- Universal, foundational

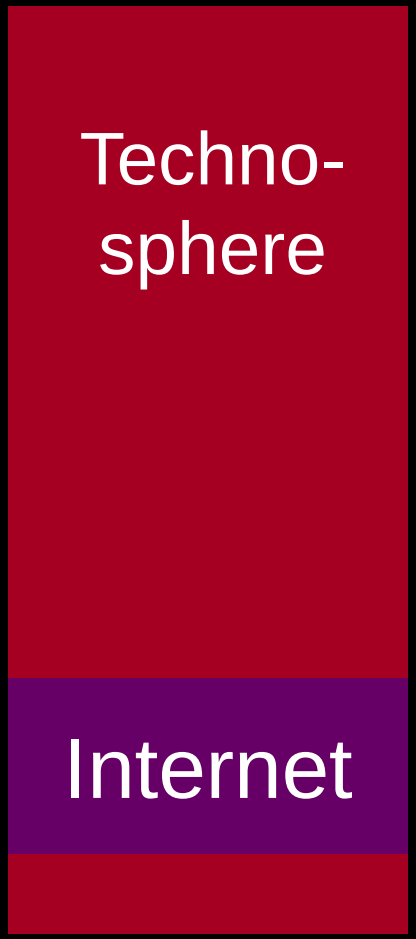


- Universal, foundational

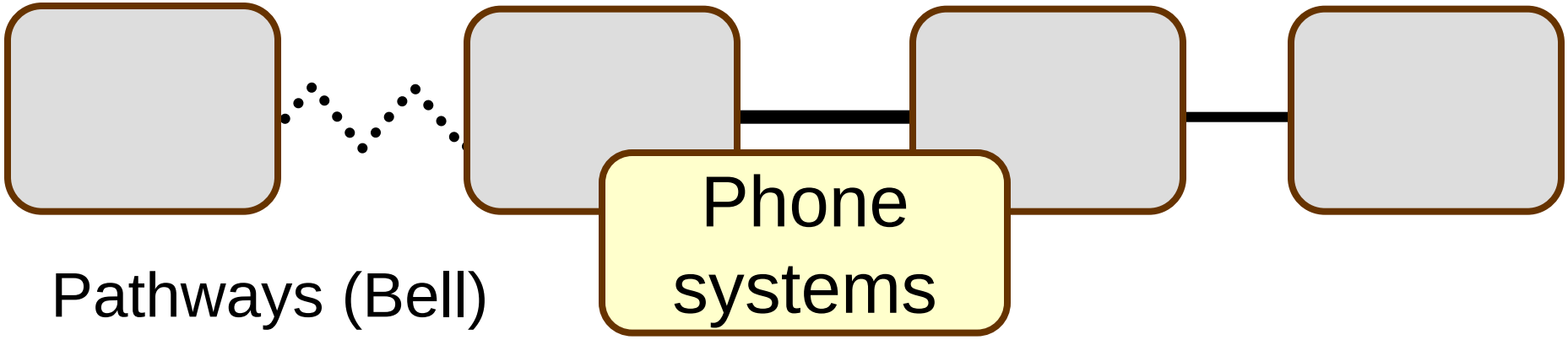


Two lines of research:

1. Patch the existing Internet architecture so it handles its new roles



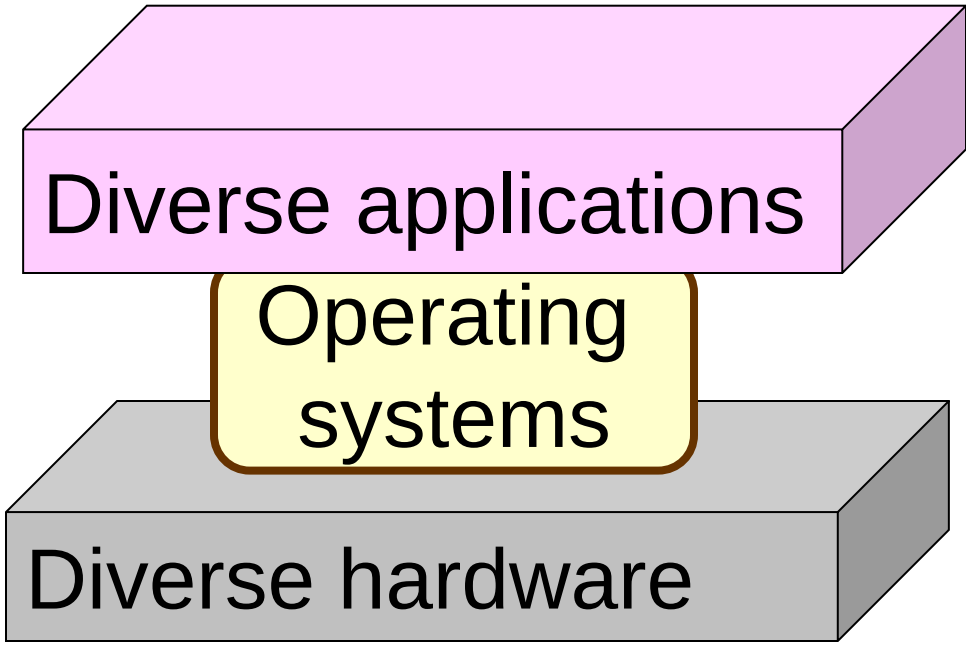
- Real time
- Control ***over*** (not just of) networks
- Action in the physical world
- Human collaborators and adversaries
- Net-centric ***everything***



Pathways (Bell)
Communications

Layers (Net)
Computer

Ancient network architecture:
“Bell-heads versus Net-heads”



Modern theory and the Internet

Levels of understanding

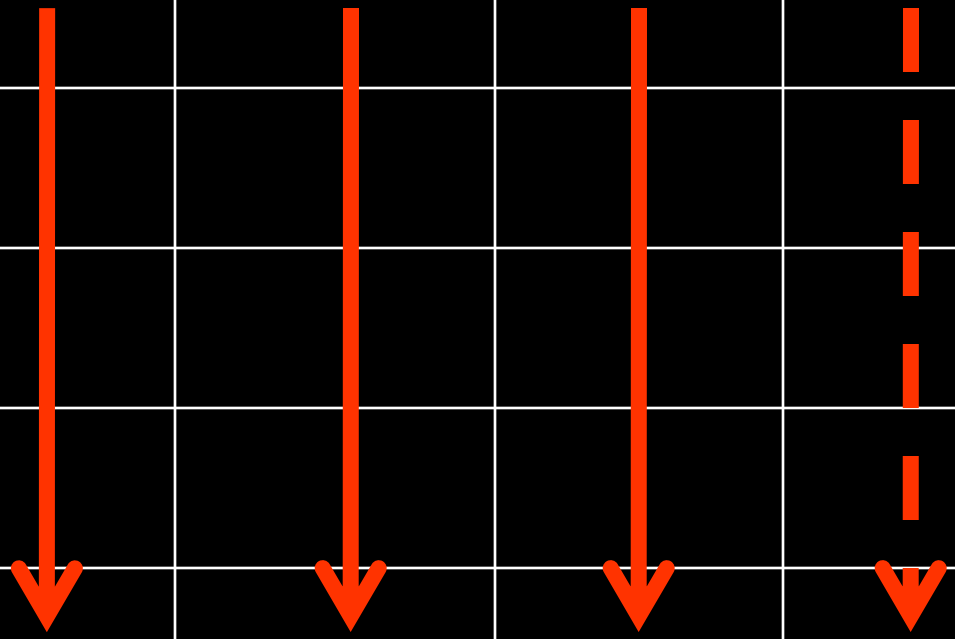
Verbal/cartoon
Data and statistics
Modeling and simulation
Analysis
Synthesis

Topics

Traffic
Topology
Control and dynamics
Layering
Architecture

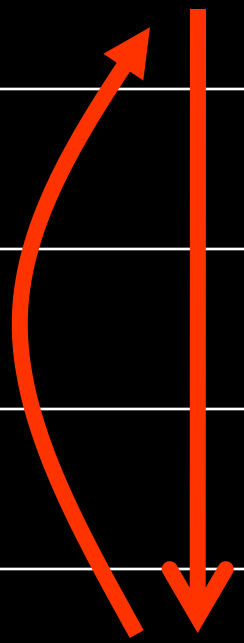
Recent progress (1995-)

	Traffic	Topology	C&D	Layering	Architect.
Cartoon					?
Data/stat					
Mod/sim					
Analysis					
Synthesis					

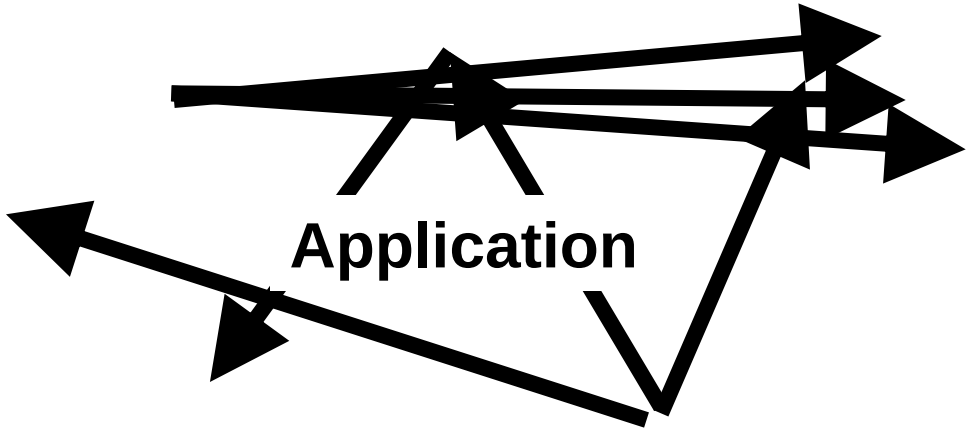


Recent progress

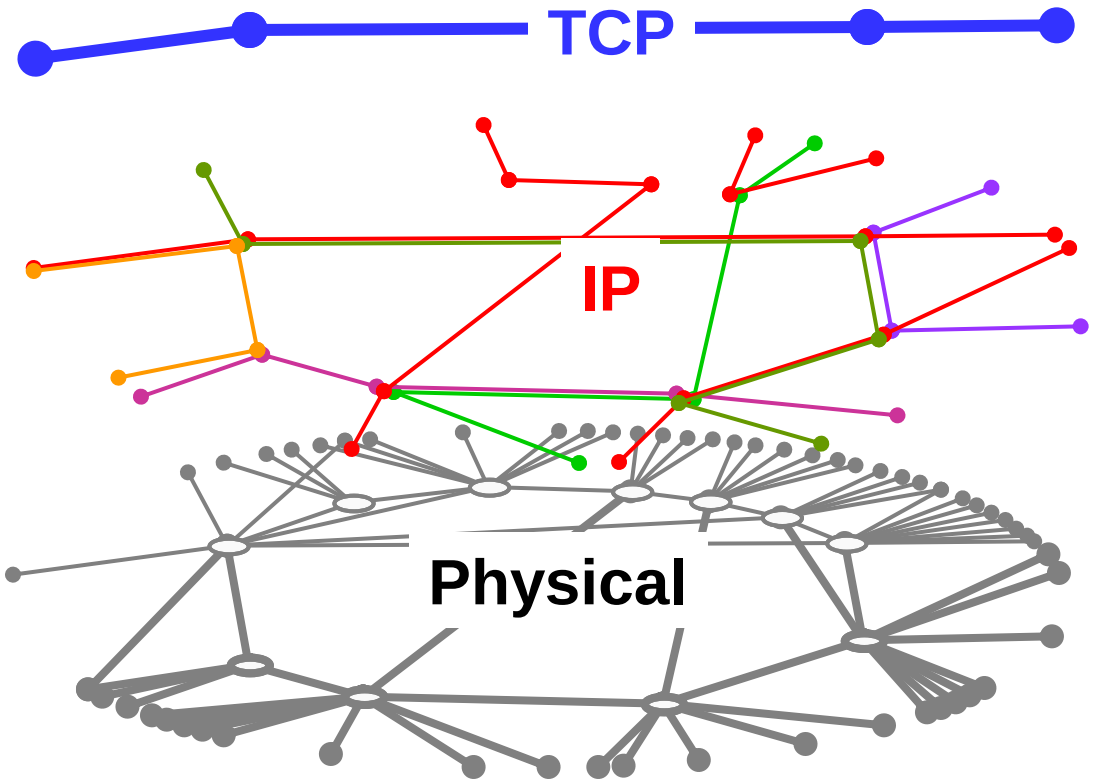
	Traffic	Topology	C&D	Layering	Architect.
Cartoon					
Data/stat					
Mod/sim					
Analysis					
Synthesis					



Architecture is ***not*** graph topology.



Architecture facilitates arbitrary graphs.



Recent progress (1995-)

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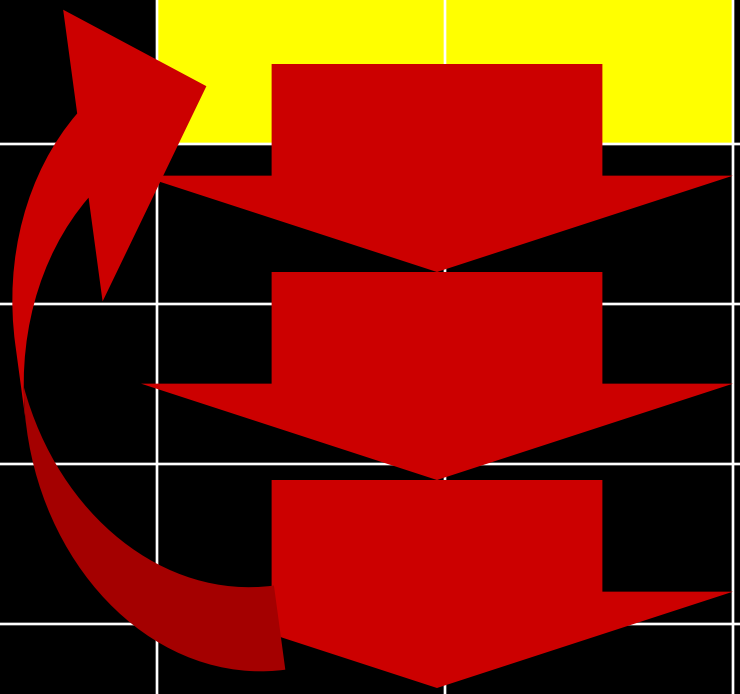
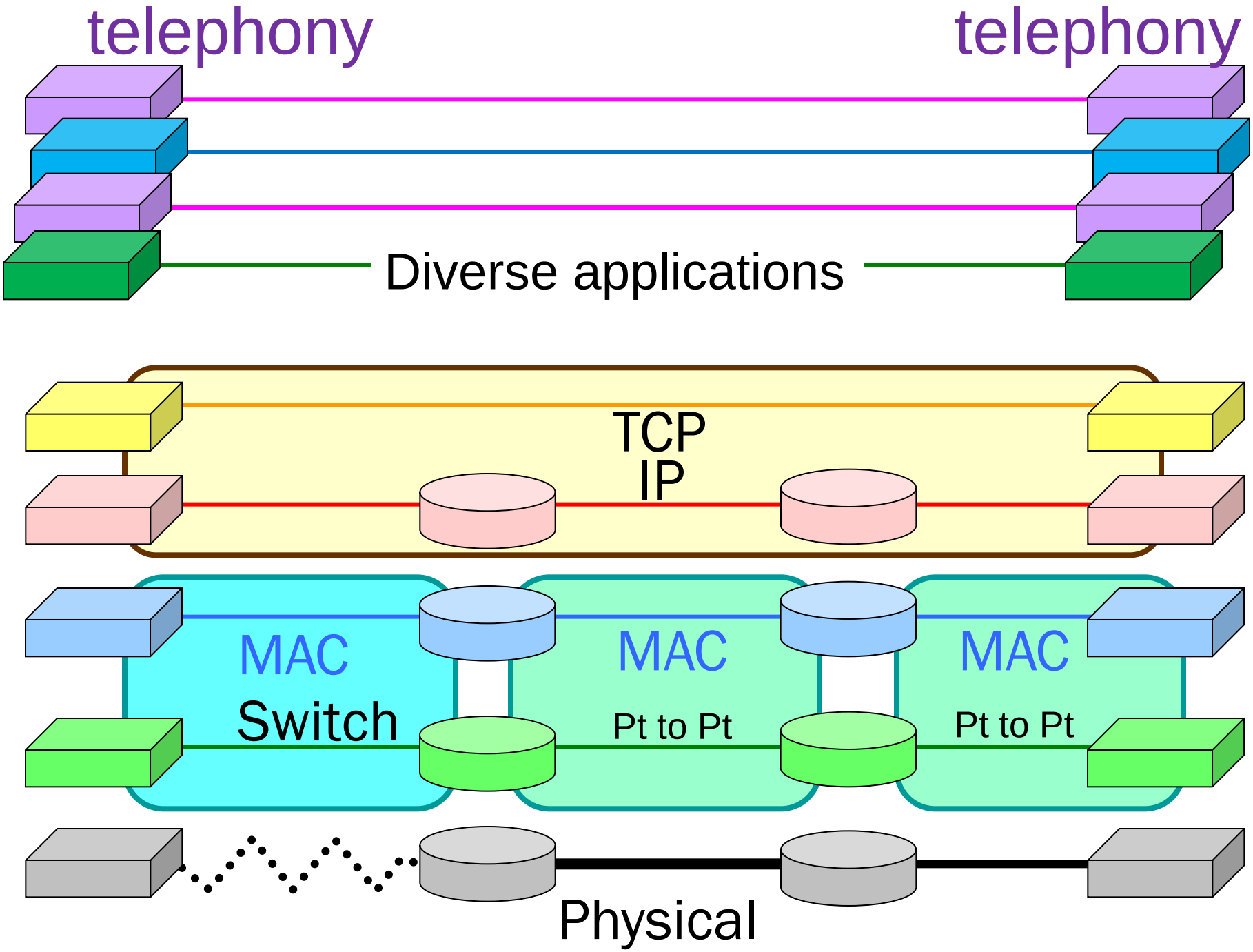



telephony
telephony
Diverse applications
TCP
IP
MAC
Switch
MAC
Pt to Pt
MAC
Pt to Pt
Physical

Theoretical framework:
Constraints that deconstrain

Applications Deconstrained

$$\min_{\mathbf{x}} \int \left\| R\tilde{\mathbf{x}} - \mathbf{c} \right\|^2 + \left\| R\mathbf{x} - \mathbf{c} \right\|^2 \, dt$$

$$\left| \tilde{\mathbf{x}} = \arg\max_{\mathbf{v}} L \;\; \mathbf{v}, \mathbf{p} \;\; , \quad \dot{\mathbf{p}} = R\mathbf{x} - \mathbf{c} \right.$$

$$\Rightarrow x_s = \arg\max_{v} L_s \;\; v, \mathbf{p}$$

Resources Deconstrained

Enormous progress

- Layering as optimization decomposition
- Optimal control
- Robust control
- Game theory
- Network coding

Theoretical framework:
Constraints that deconstrain

Enormous progress

- Layering as optimization
- Optimal control
- Robust control
- Game theory
- Network coding

- Many robustness issues left unaddressed
- Secure, verifiable, manageable, maintainable, etc
- Architecture/policy, not part of control/dynamics
- How to expand the theory?

Cyber-Physical Theories?

- Thermodynamics
- Communications
- Control
- Computation

- Same robustness issues still unaddressed
- Architecture/policy, not part of any of these
- Each assumes an architecture a priori
- How to expand the theory?

Cyber

- Thermodynamics
- Communications
- Control
- Computation

Physical

- Thermodynamics
- Communications
- Control
- Computation

Internet

Bacteria

Case studies motivate integration

Cyber

- Thermodynamics
- Communications
- Control
- Computation

Physical

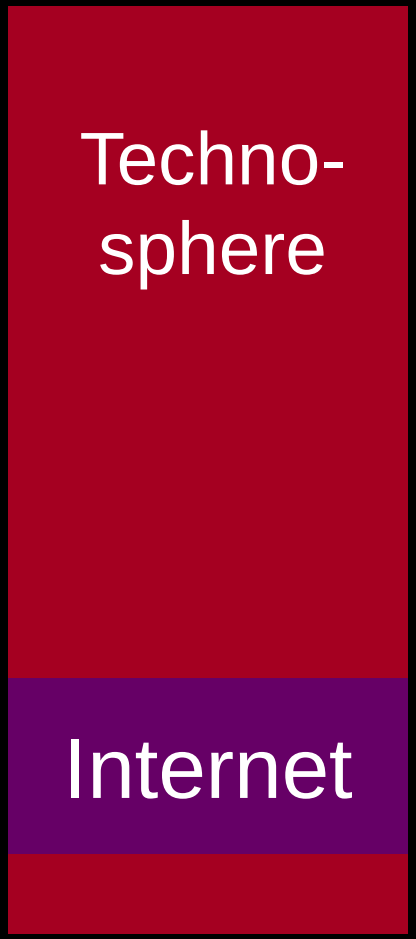
- Thermodynamics
- Communications
- Control
- Computation

Promising unifications

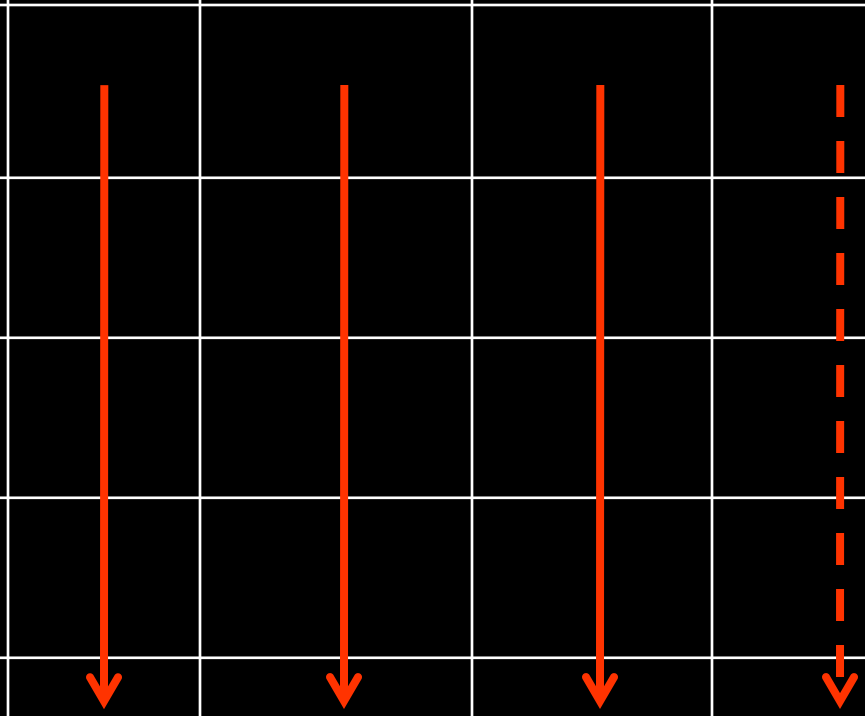
A start but more is needed

Two lines of research:

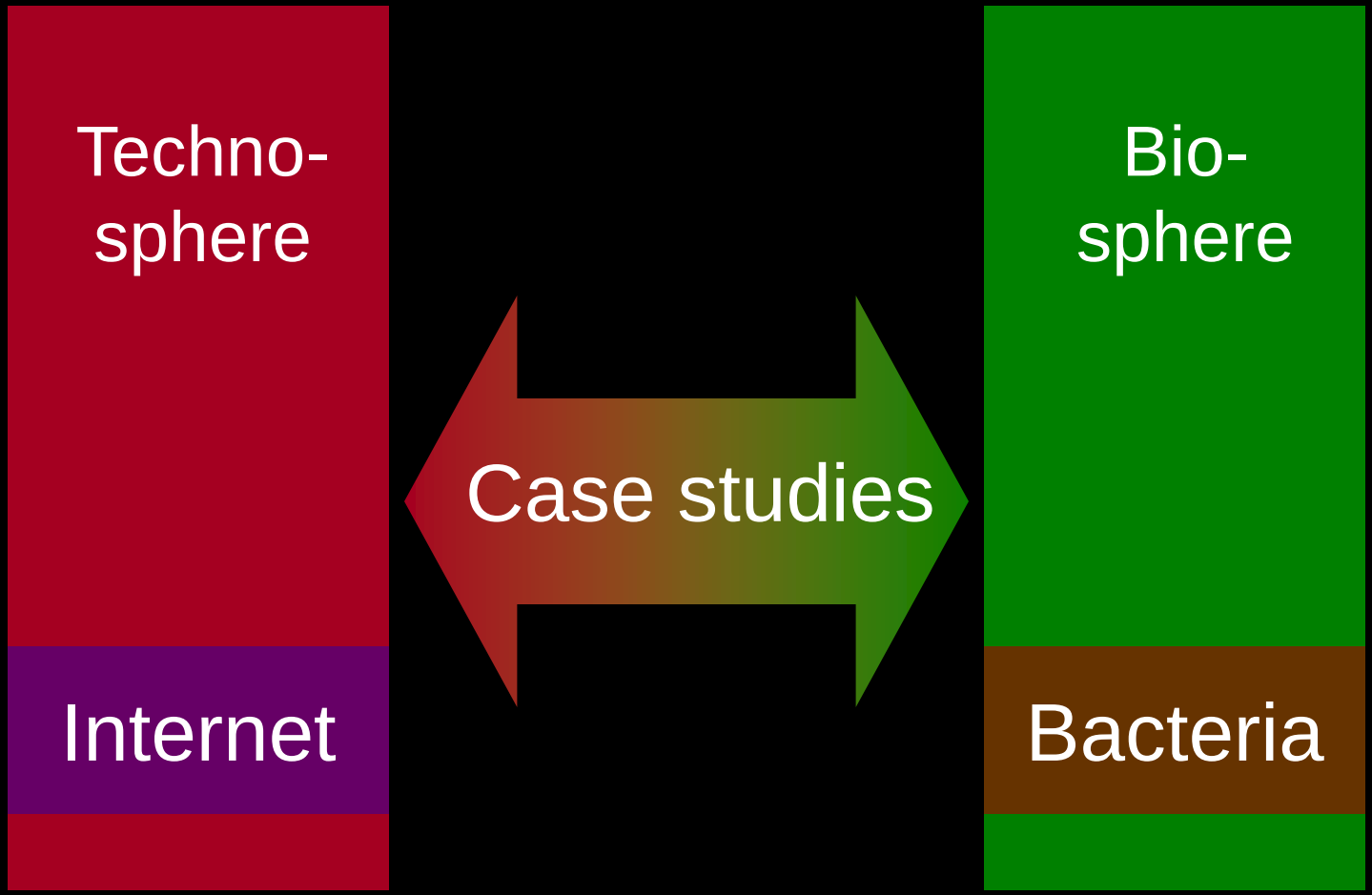
1. Patch the existing Internet architecture
2. Fundamentally rethink network architecture



Architecture?

	Traffic	Topology	C&D	Layering	**Architect.**
Cartoon					**?**
Data/stat					
Mod/sim					
Analysis					
Synthesis					

1.
2. Fundamentally rethink network architecture



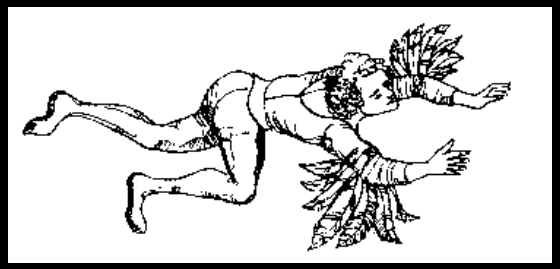
Biology versus the Internet

Similarities

- Evolvable architecture
- Robust yet fragile
- Constraints/deconstrain
- Layering, modularity
- Hourglass with bowties
- Feedback
- Dynamic, stochastic
- Distributed/decentralized
- ***Not*** scale-free, edge-of-chaos, self-organized criticality, etc

Differences

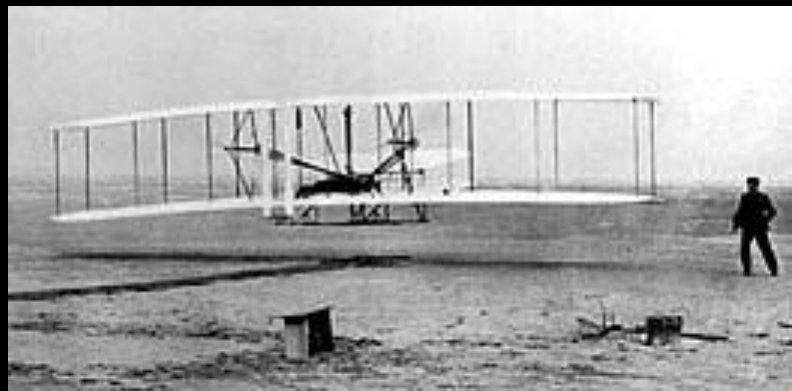
- Metabolism
- Materials and energy
- Autocatalytic feedback
- Feedback complexity
- Development and regeneration
- >4B years of evolution
- How the parts work?



The dangers of naïve biomemetics

Feathers and flapping?

Or lift, drag, propulsion, and ***control***?



Getting it (W)right, 1901

- "We know how to construct airplanes." (lift and drag)
- "Men also know how to build engines." (propulsion)
- "Inability to balance and steer still confronts students of the flying problem." (control)
- "When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance."

Wilbur Wright on Control, 1901

Getting it right, 2010, Control++ Architecture, networks, robustness, and complexity

- Words we use all the time
- Often as their own antonym
- Thus potential sources of confusion
- Today: discuss a few basic ideas that seem necessary
- Illustrate with familiar examples

Biology versus the Internet

Similarities

- Evolvable architecture
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Differences

- **Metabolism**
- **Materials and energy**
- Autocatalytic feedback
- Feedback complexity
- Development and regeneration
- >4B years of evolution

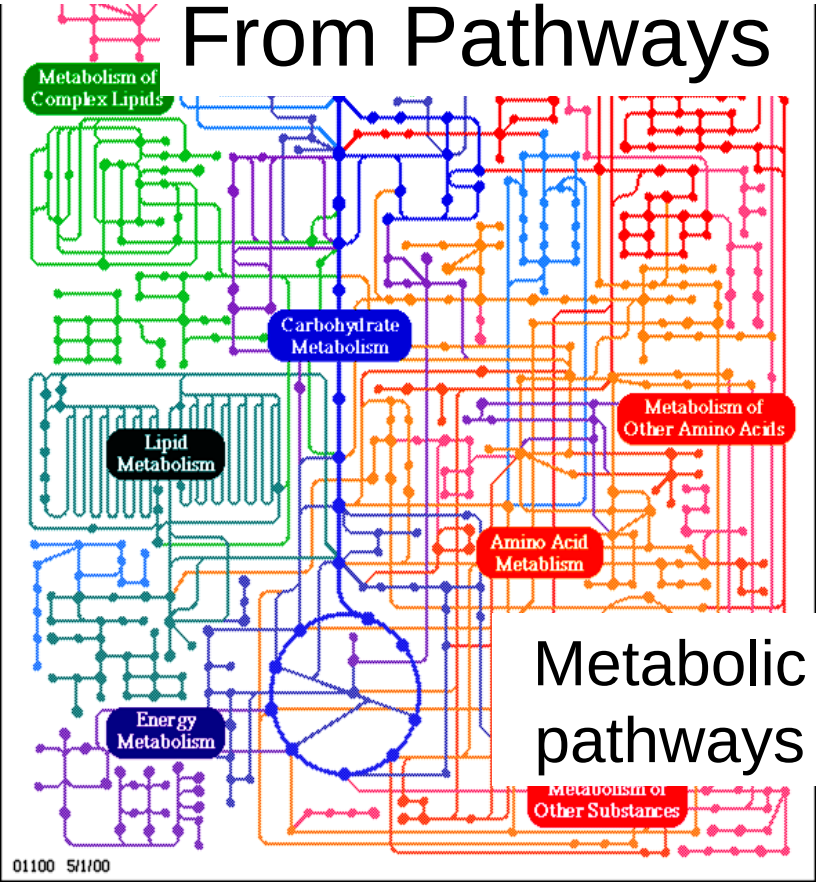
Focus on bacterial biosphere

“Central dogma”

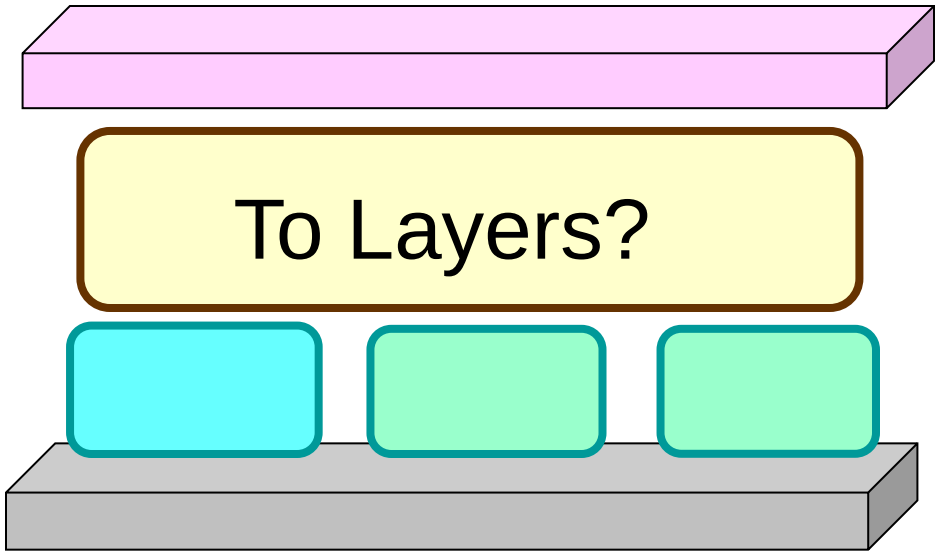
DNA → RNA → Protein

Network architecture?

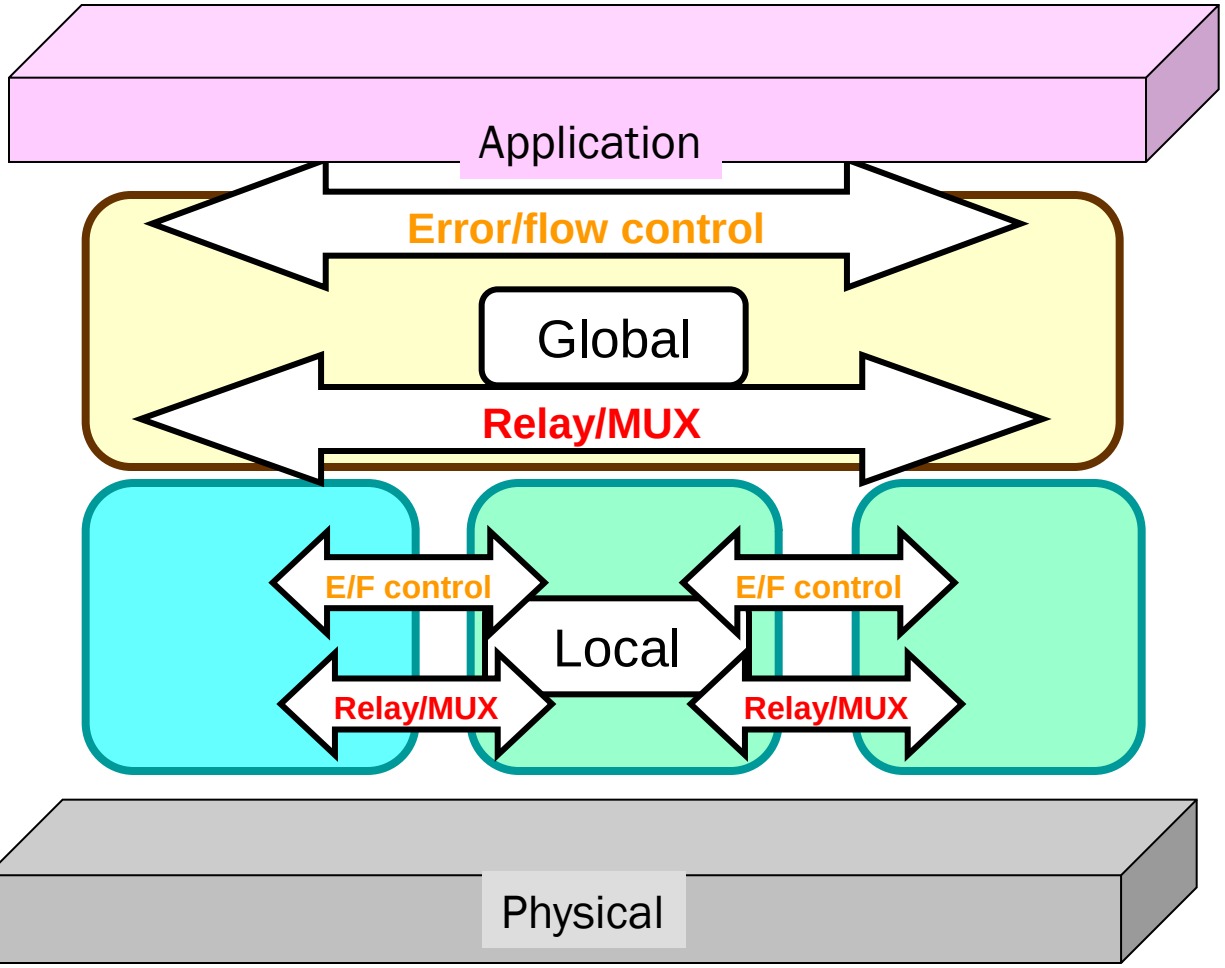
From Pathways



Metabolic pathways



Recursive control structure



Reactions
Flow
Protein level

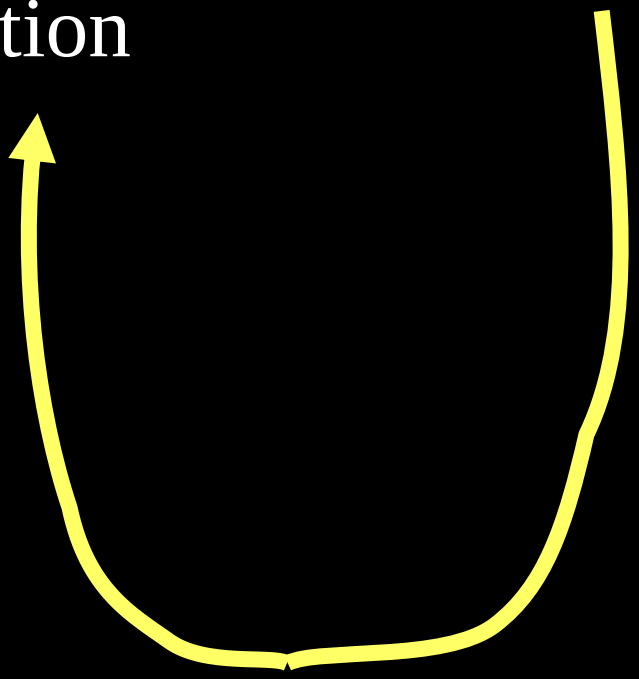
Reactions
Flow
RNA level

Reactions
Flow
DNA level

In the real (vs virtual) world

What matters:

- Action

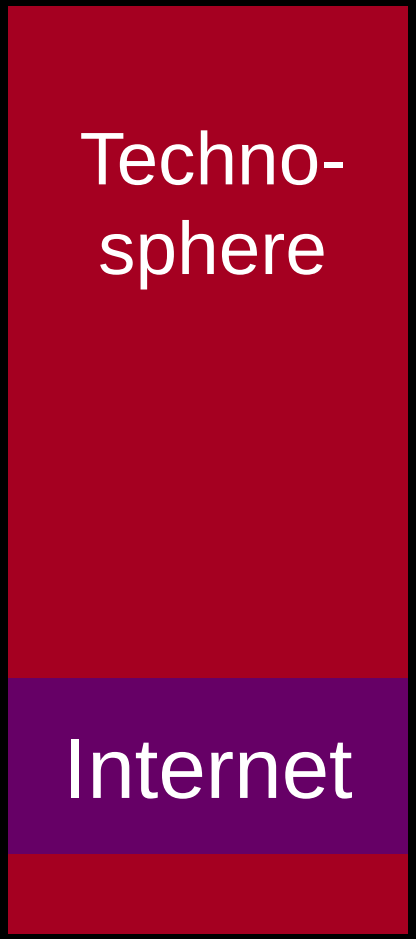


What doesn’t:

- Data
- Information
- Computation
- Learning
- Decision
- …

Two lines of research:

1. Patch the existing Internet architecture
2. Fundamentally rethink network architecture



Human complexity?

Robustness?

Fragility?

Human complexity

Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Healing wound /infect	☹ AutoImmune/Inflame

Mechanism?

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect
  - ☹ Fat accumulation
  - ☹ Insulin resistance
  - ☹ Proliferation
  - ☹ Inflammation

Fragile

- ☹ Obesity, diabetes
- ☹ Cancer
- ☹ AutoImmune/Inflame
  - ☹ Fat accumulation
  - ☹ Insulin resistance
  - ☹ Proliferation
  - ☹ Inflammation

What's the difference?

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect

Fragile

- ☹ Obesity, diabetes
- ☹ Cancer
- ☹ AutoImmune/Inflame

- ☹ Fat accumulation
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- ☹ Inflammation

Static energy

Accident or necessity?

What's the difference?

Robust

- ☺ Metabolism
- ☺ Regeneration & repair
- ☺ Healing wound /infect

Fragile

- ☹ Obesity, diabetes
- ☹ Cancer
- ☹ AutoImmune/Inflame

- ☹ Fat accumulation
- ☹ Insulin resistance
- ☹ Proliferation
- ☹ Inflammation

Controlled
Dynamic

Low mean
High variability

Uncontrolled
Chronic

High mean
Low variability

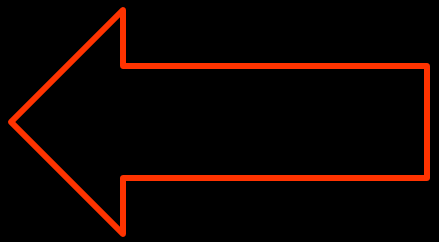
Restoring robustness

Robust

Fragile

Controlled
Dynamic

Low mean
High variability



Uncontrolled
Chronic

High mean
Low variability

Human complexity

Robust	Yet Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regeneration & repair	☹ Cancer
☺ Microbe symbionts	☹ Parasites, infection
☺ Immune/inflammation	☹ AutoImmune/Inflame
☺ Neuro-endocrine	☹ Addiction, psychosis…
🗐 Complex societies	☠ Epidemics, war…
🗐 Advanced technologies	💣 Catastrophes
🗐 Risk “management”	💣 Obfuscate, amplify,…

Accident or necessity?

Robust	Fragile
☺ Metabolism	☹ Obesity, diabetes
☺ Regenerati	
☺ Healing wo	une/Inflame

☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

- Fragility ← Hijacking, side effects, unintended…
- Of mechanisms evolved for robustness
- Complexity ← control, robust/fragile tradeoffs
- Math: New robust/fragile conservation laws

Both

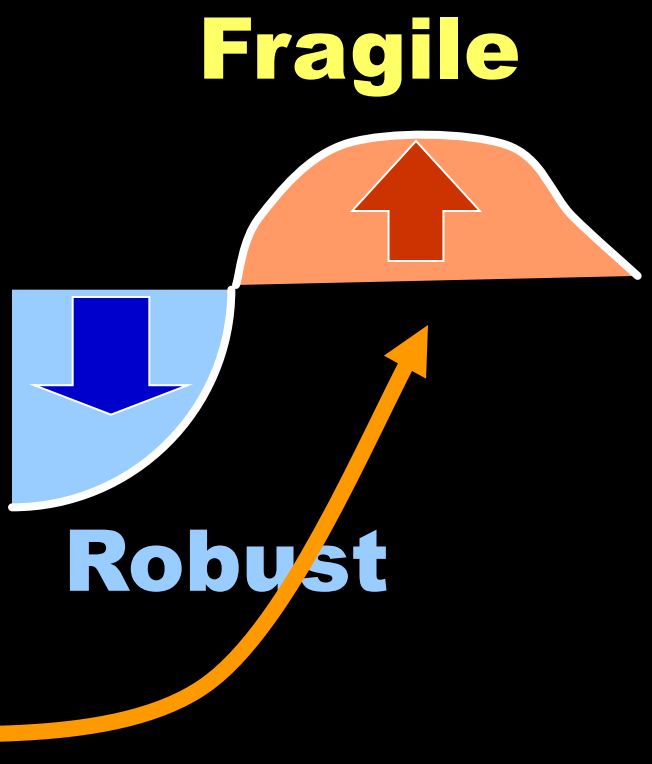
Accident or necessity?

[a system] can have
[a property] ***robust*** for
[a set of perturbations]

Yet be ***fragile for***

[a different property]

Or [a different perturbation]



Robust yet fragile = fragile robustness

[a system] can have
[a property] ***robust*** for
[a set of perturbations]

Apply recursively

[property] = ***robust*** for
[one set of perturbations]

[a property]

fragile for

[another property] or
[another set of perturbations]

[a perturbation]

Robust yet fragile = fragile robustness

[a system] can have
[a property] ***robust*** for
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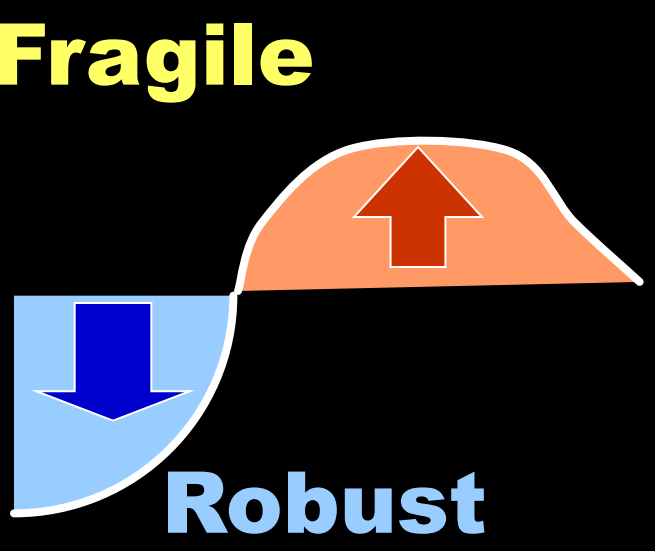
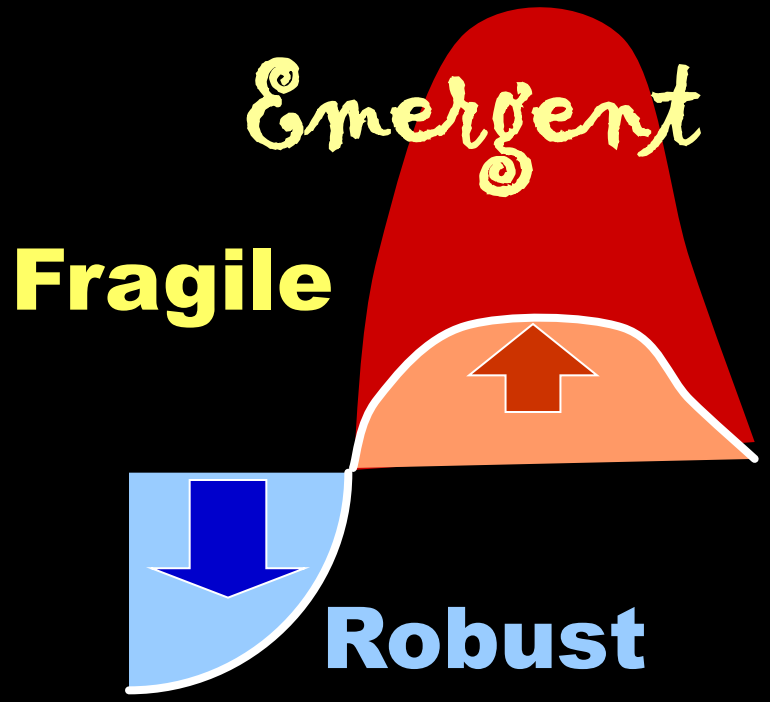


- Some fragilities are inevitable in robust complex systems.

- But if robustness/fragility are ***conserved***, what does it mean for a ***system*** to be robust or fragile?



• Some fragilities are inevitable in robust complex systems.

• But if robustness/fragility are ***conserved***, what does it mean for a ***system*** to be robust or fragile?

• Robust ***systems*** systematically manage this tradeoff.
• Fragile ***systems*** waste robustness.

Definition: Resilience?

- Resilient systems effectively manage fragility tradeoffs?

- How does architecture facilitate resilience?

Robust

- ☺ **Metabolism**
- ☺ Regeneration & repair
- ☺ Healing wound /infect

- Fragility ← Hijacking, side effects, unintended…
- Of mechanisms evolved for robustness
- Complexity ← control, robust/fragile tradeoffs
- **Math: New robust/fragile conservation laws**

Mechanism?

Robust

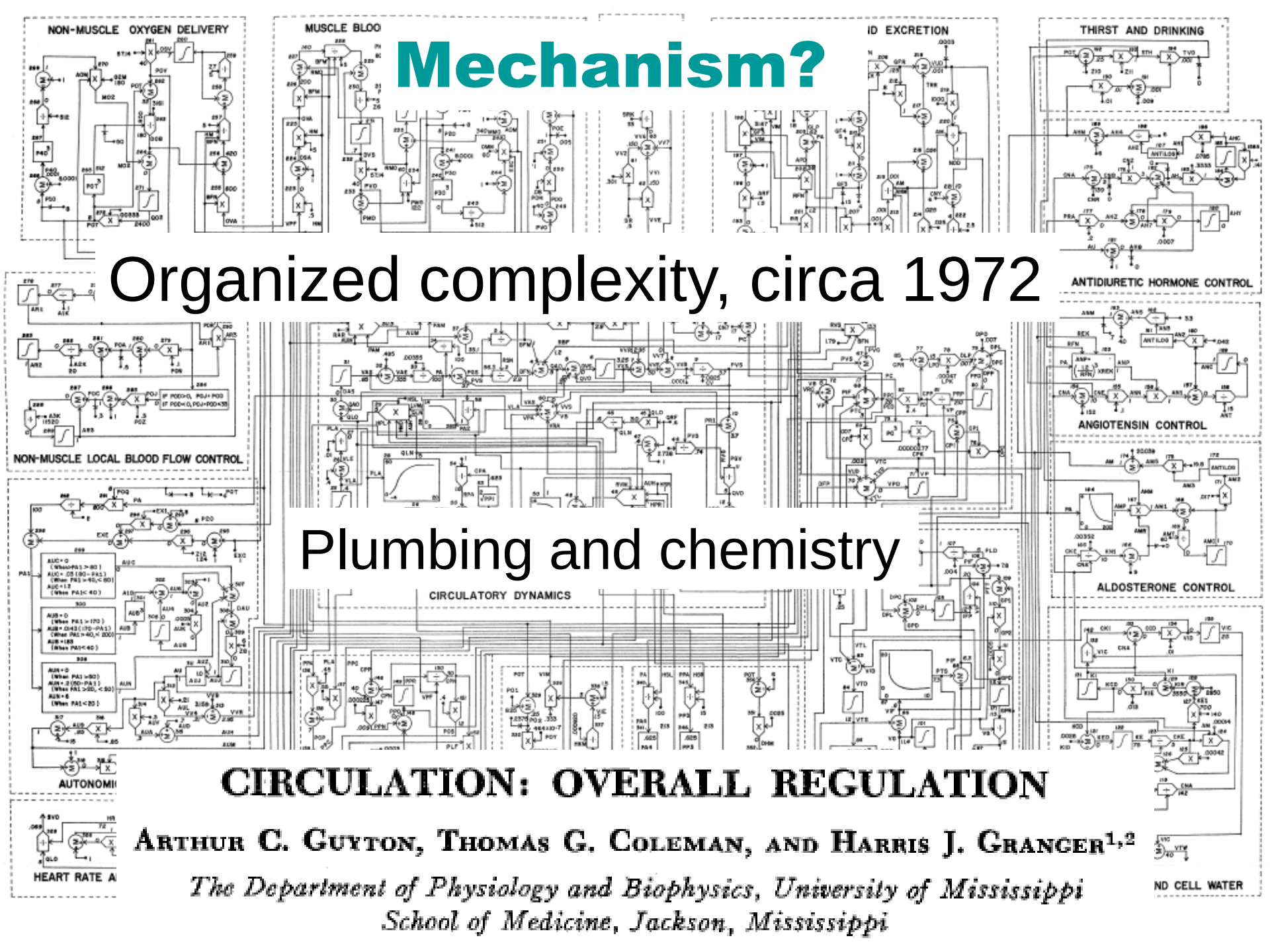
☺ Metabolism
☺ Regeneration & repair
☺ Healing wound /infect

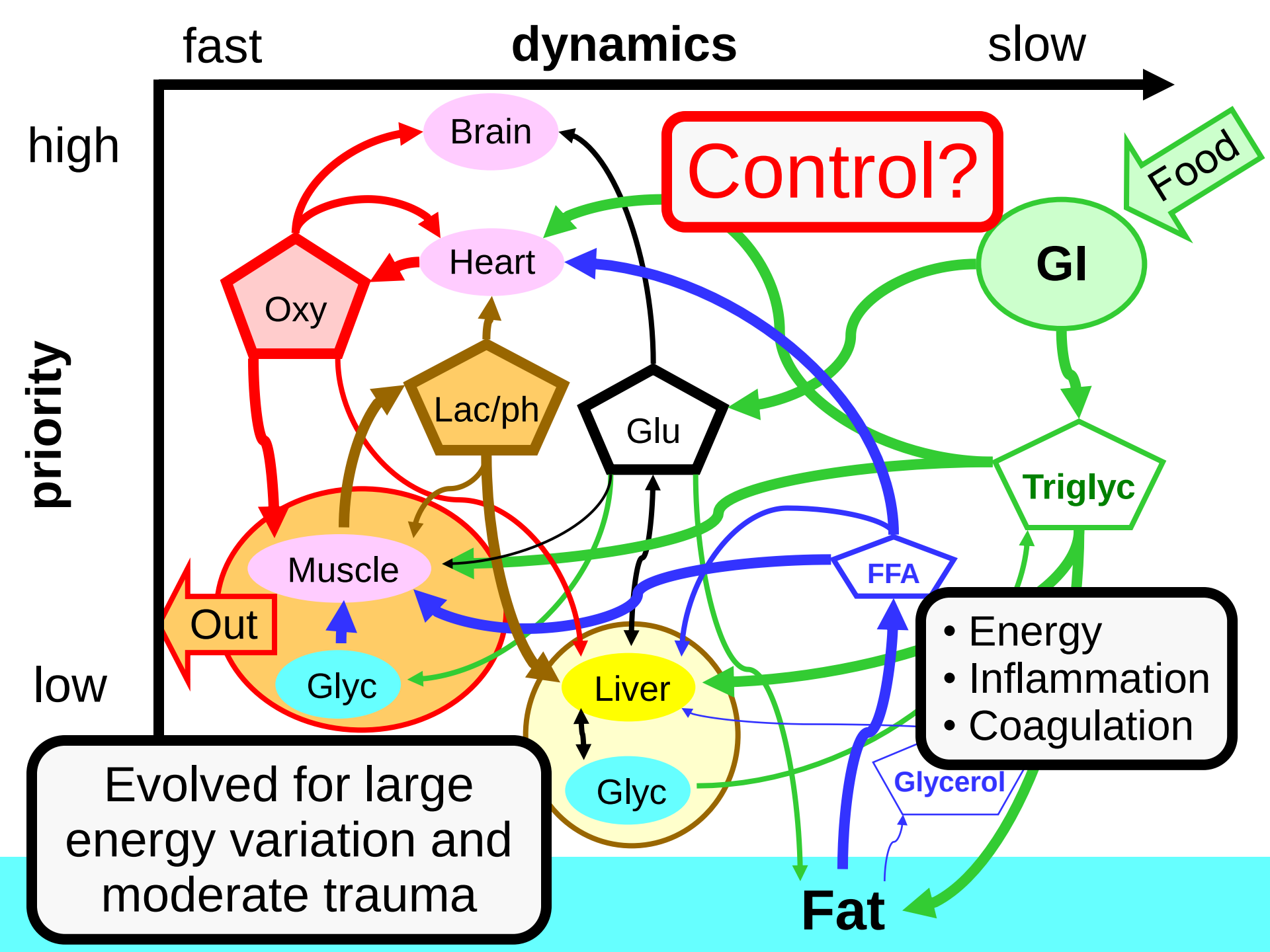
☹ Fat accumulation
☹ Insulin resistance
☹ Proliferation
☹ Inflammation

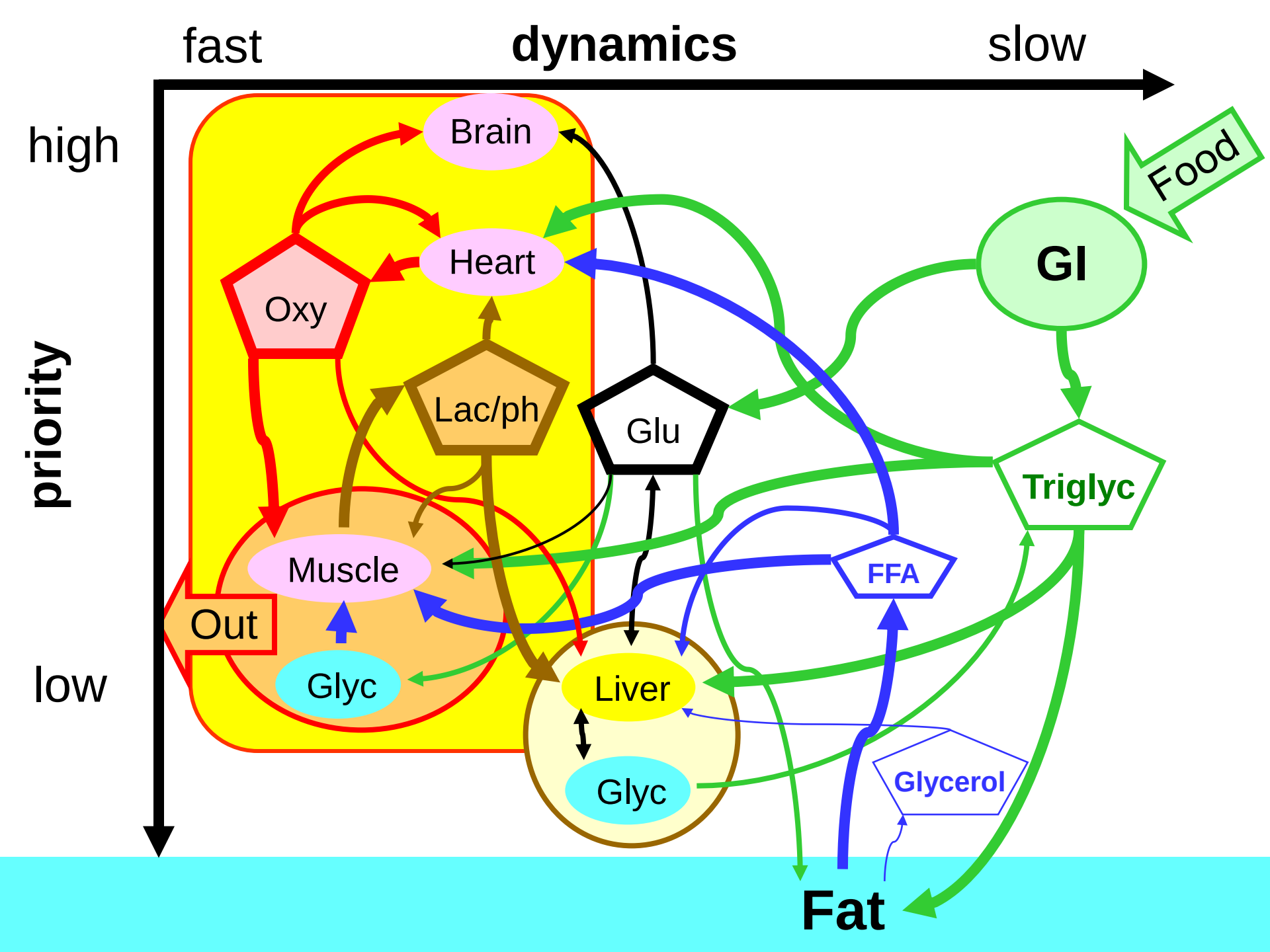
Controlled
Dynamic

Low mean
High variability

Fluctuating energy


Mechanism?
Organized complexity, circa 1972
Plumbing and chemistry
NON-MUSCLE OXYGEN DELIVERY
ID EXCRETION
THIRST AND DRINKING
ANTIDIURETIC HORMONE CONTROL
NON-MUSCLE LOCAL BLOOD FLOW CONTROL
ANGIOTENSIN CONTROL
CIRCULATORY DYNAMICS
ALDOSTERONE CONTROL
AUTONOMI
HEART RATE A
ND CELL WATER
CIRCULATION: OVERALL REGULATION
ARTHUR C. GUYTON, THOMAS G. COLEMAN, AND HARRIS J. GRANGER[1,2]
The Department of Physiology and Biophysics, University of Mississippi
School of Medicine, Jackson, Mississippi


fast
dynamics
slow
high
priority
low
Brain
Heart
Oxy
Lac/ph
Glu
Control?
Food
GI
Triglyc
FFA
Glycerol
Muscle
Out
Glyc
Liver
Glyc
Fat
• Energy
• Inflammation
• Coagulation
Evolved for large energy variation and moderate trauma


fast
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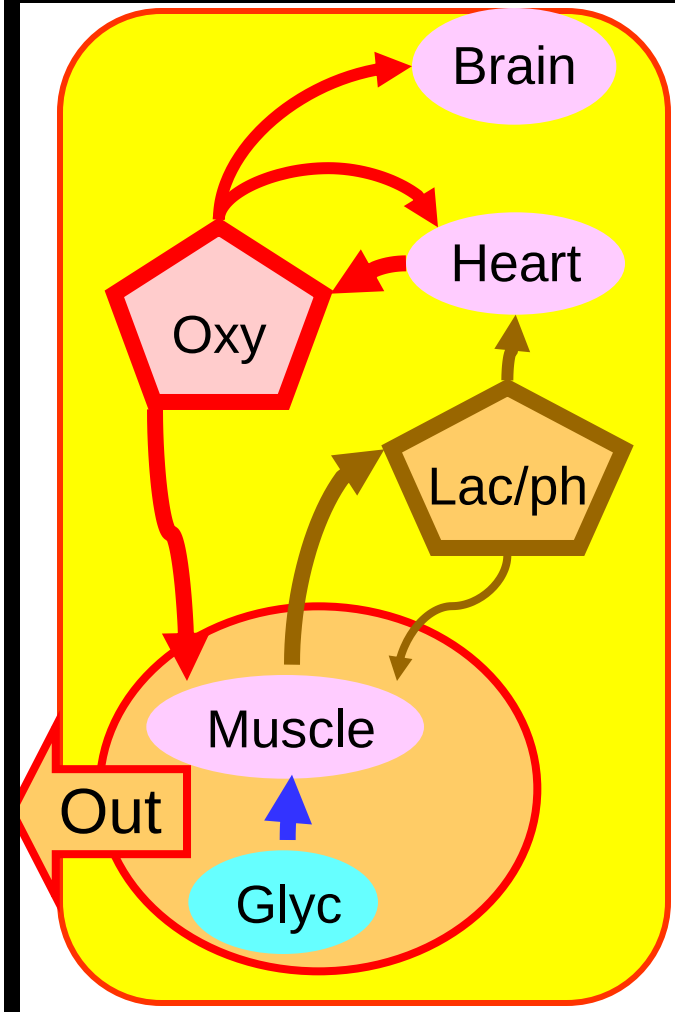
Food
GI
Triglyc
FFA
Glycerol
Fat

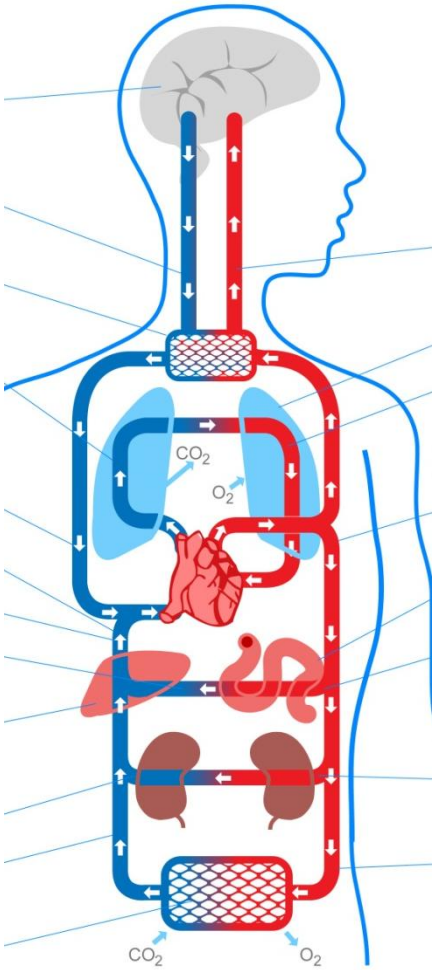
fast **dynamics** slow

high

priority

low

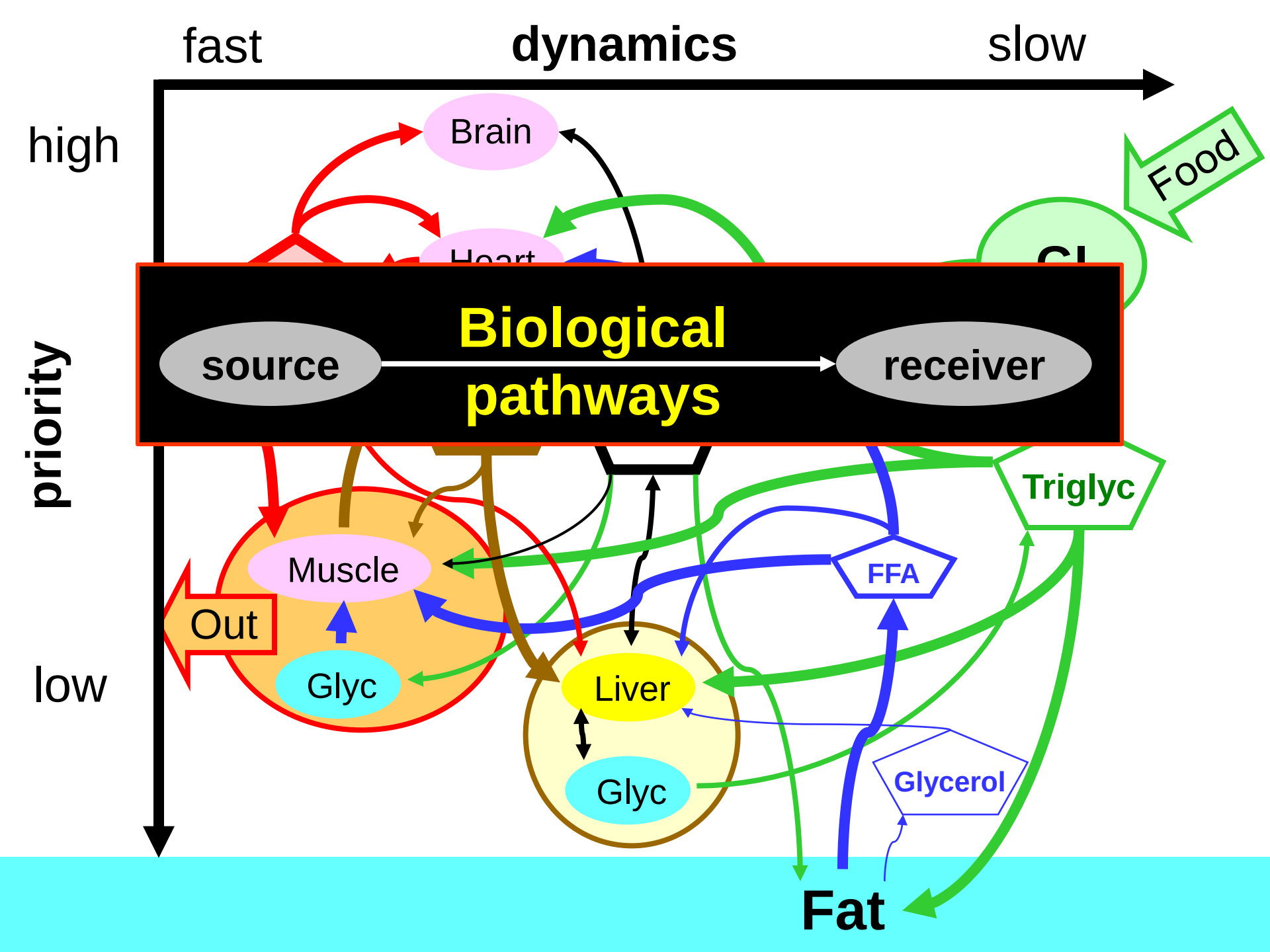




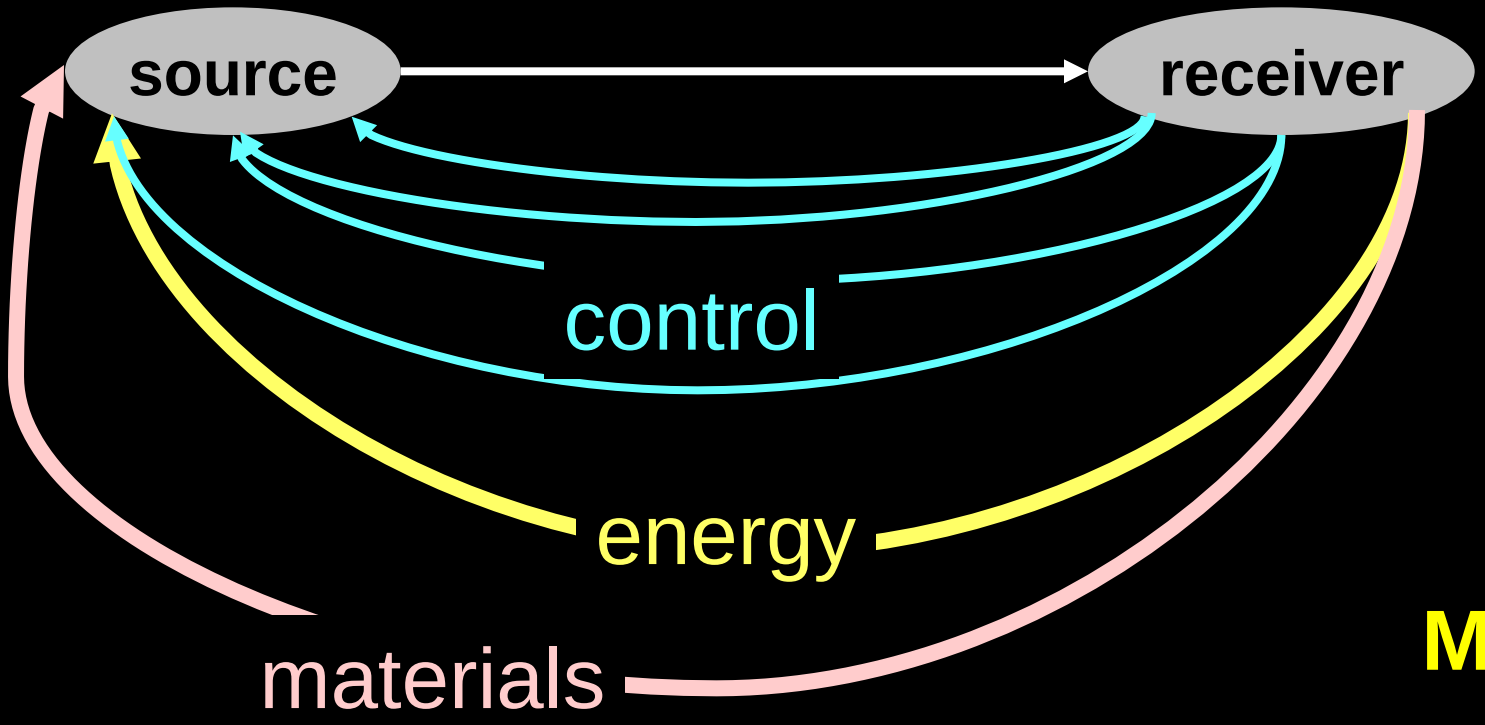
Brain is crucial element

signaling
gene expression
metabolism
lineage

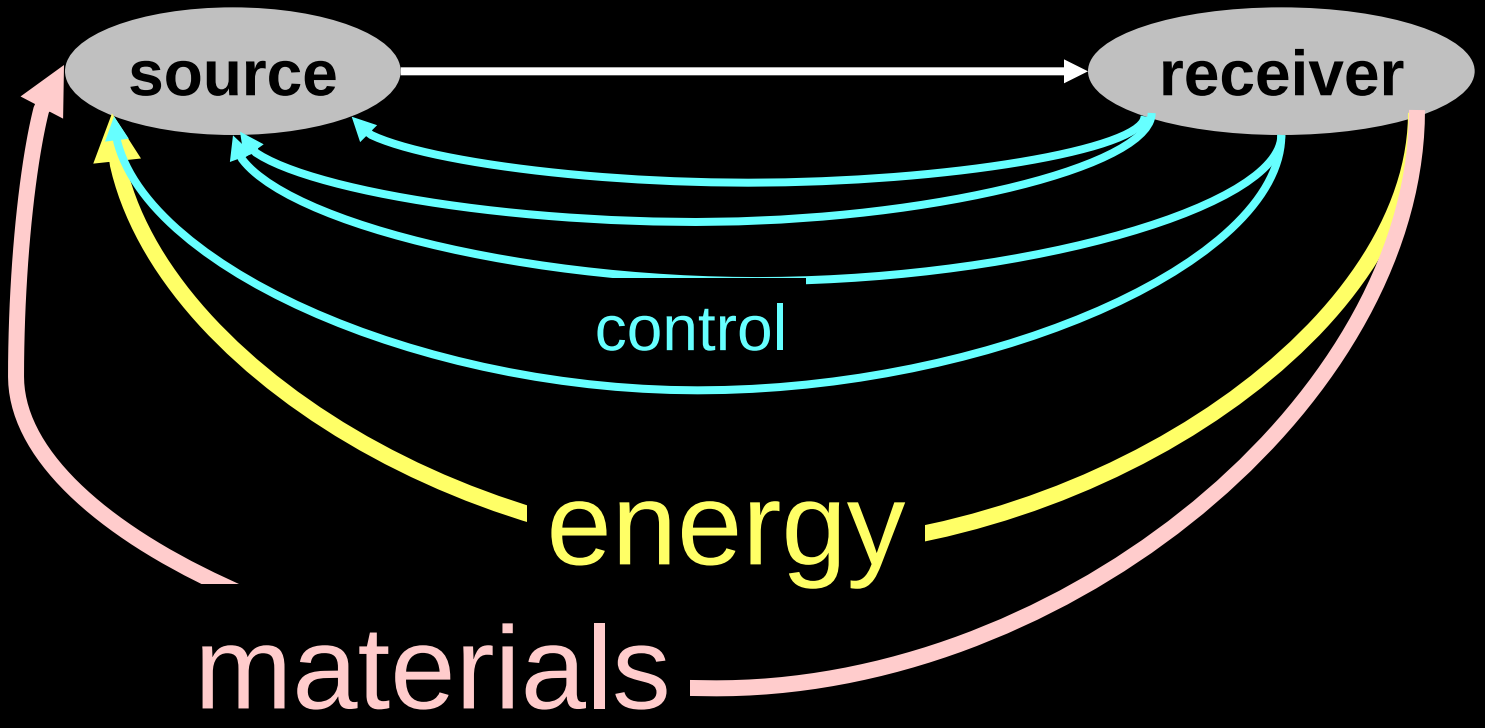
Biological pathways


fast
dynamics
slow
high
priority
low
Brain
Food
Biological
pathways
source
receiver
Triglyc
Muscle
Out
Glyc
FFA
Liver
Glyc
Glycerol
Fat

signaling
gene expression
metabolism
lineage

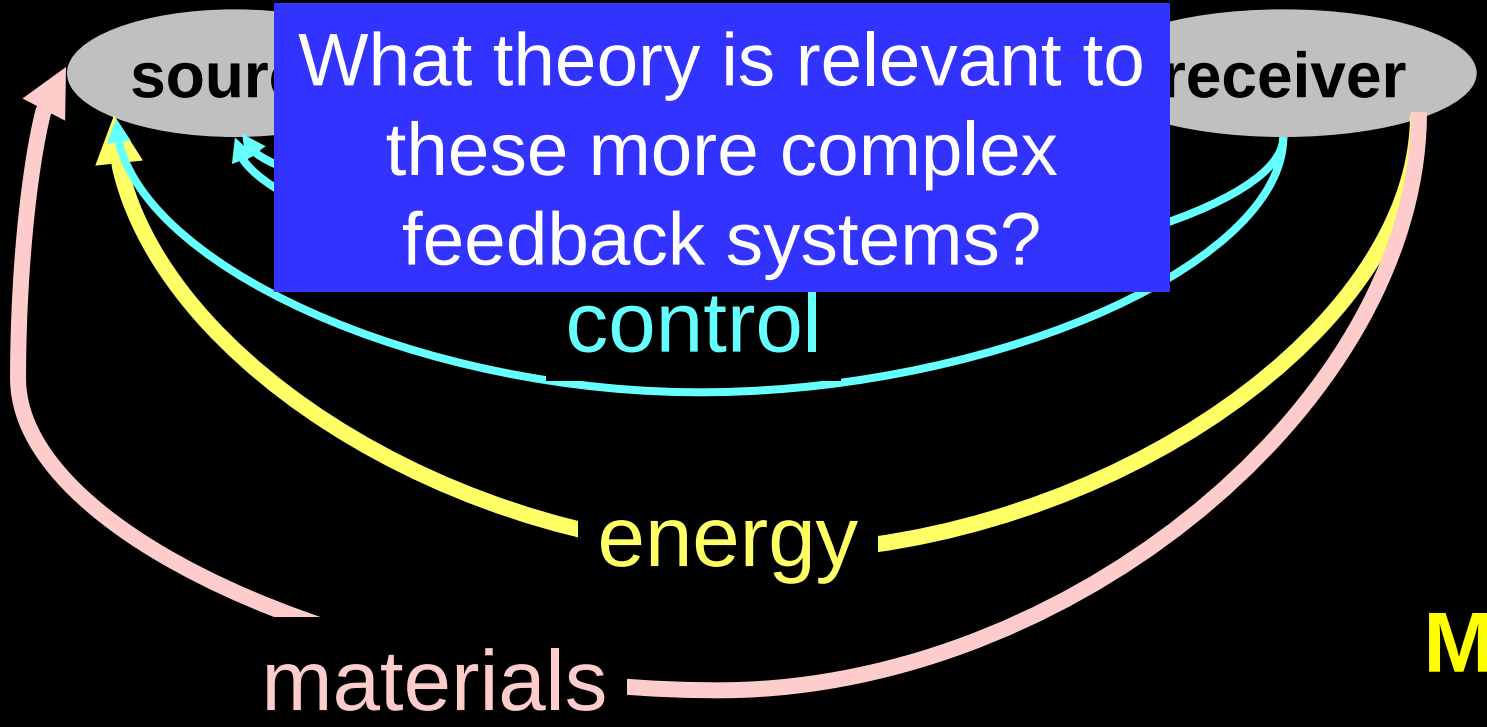


More complex feedback

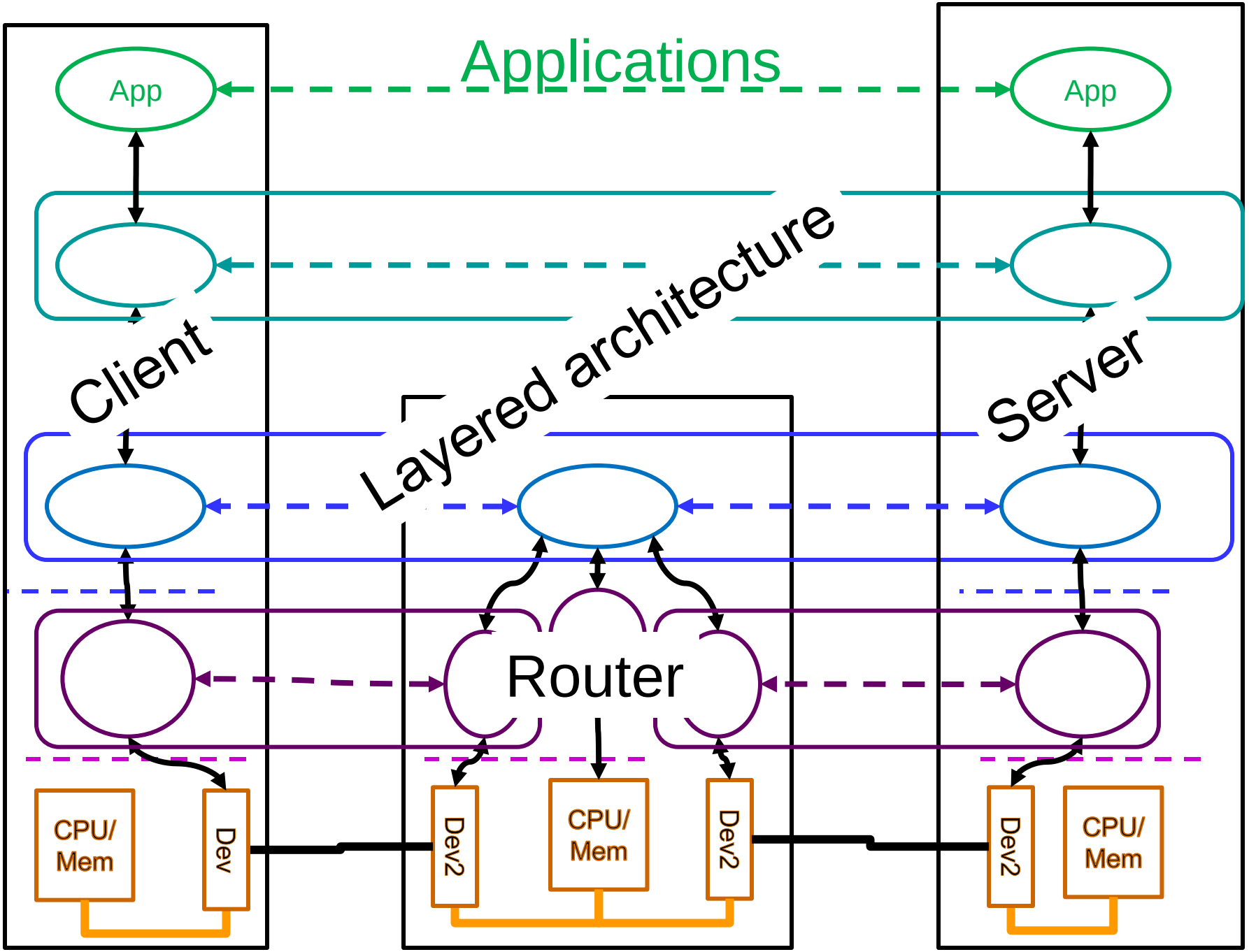


Autocatalytic feedback

signaling
gene expression
metabolism
lineage



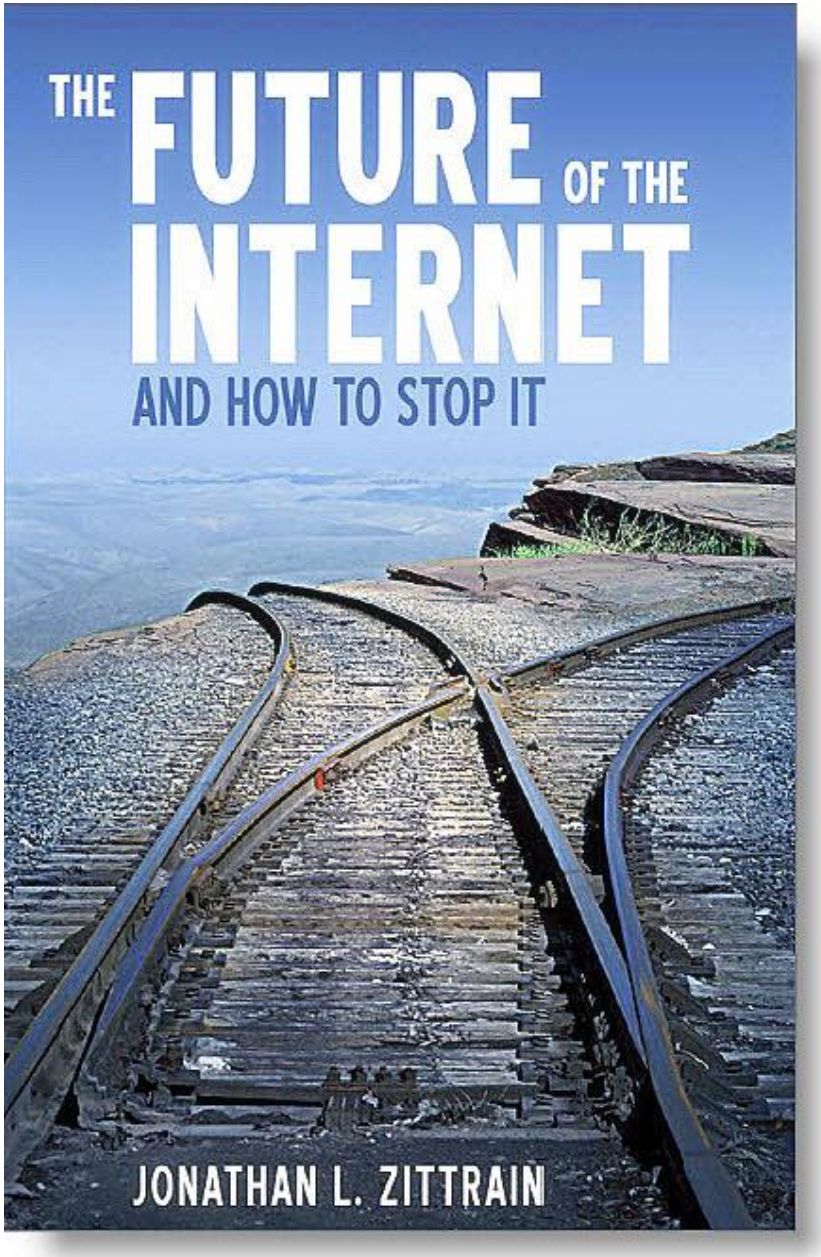
More complex feedback


Applications
App
App
Client
Layered architecture
Server
Router
CPU/
Mem
Dev
Dev2
CPU/
Mem
Dev2
Dev2
CPU/
Mem

Architectures

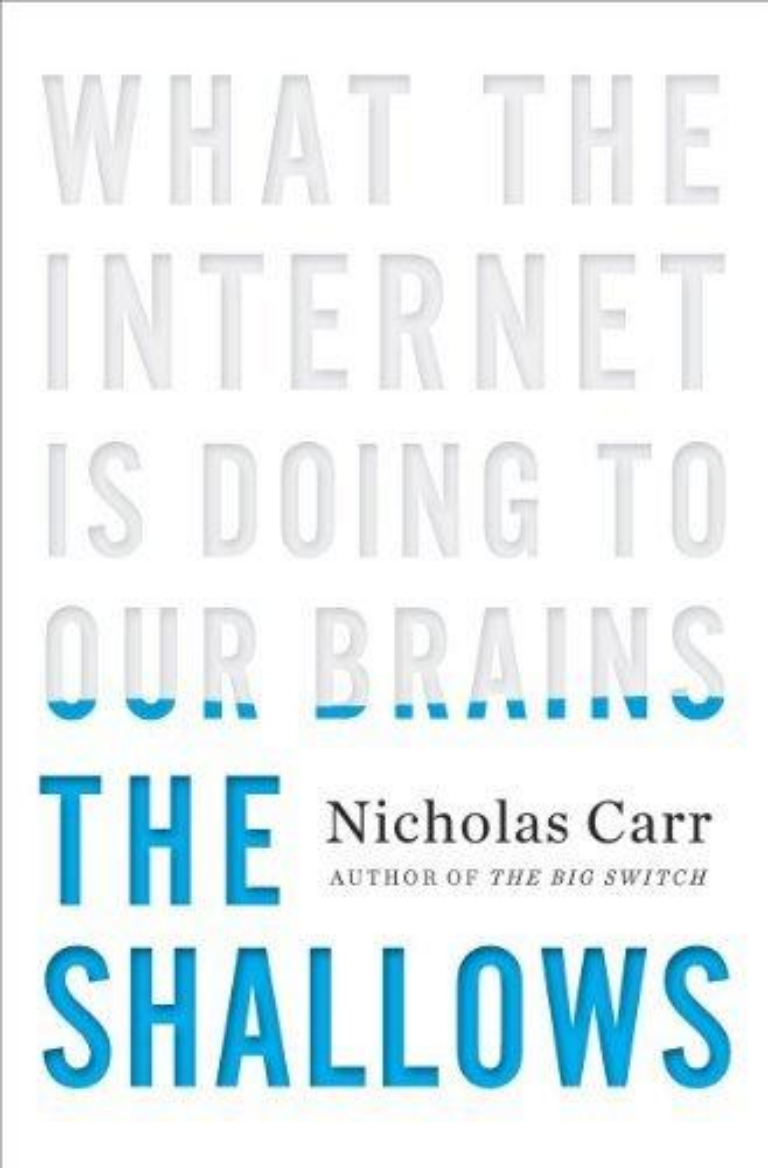
- Case studies
  - Internet
  - Bacterial biosphere
- Principles, foundations
- Theory

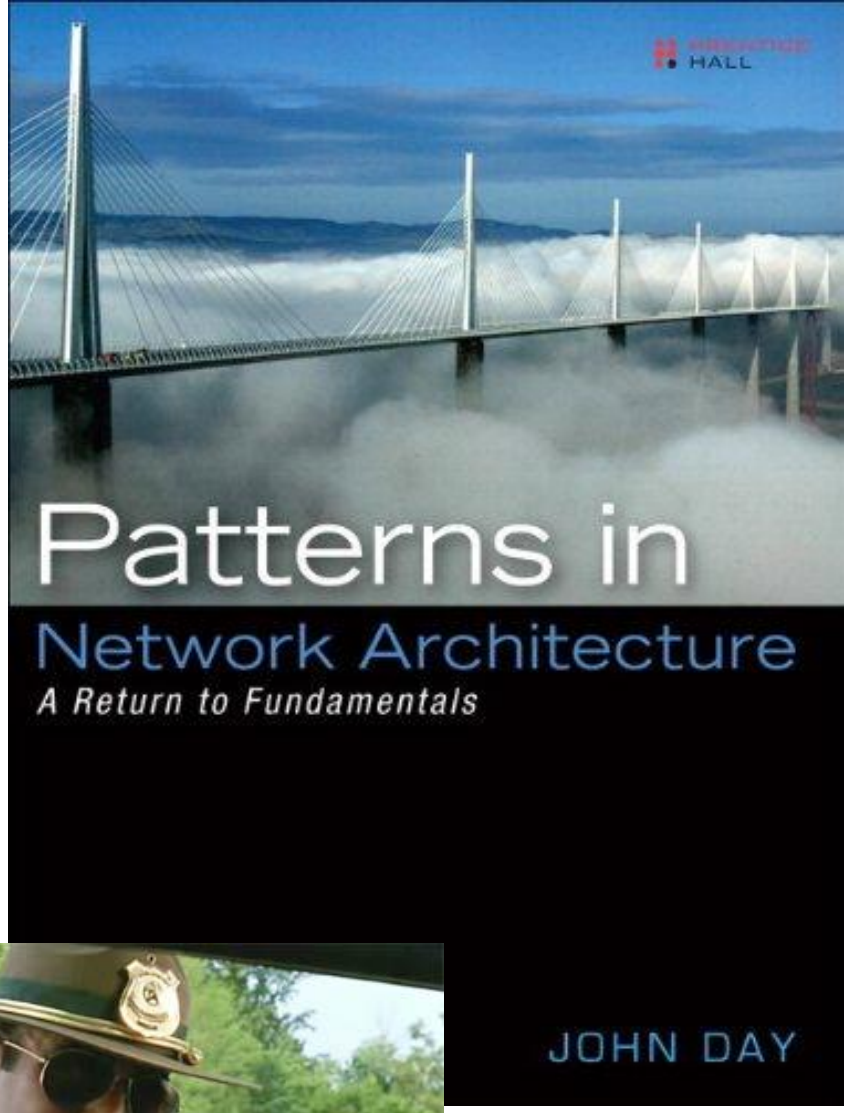
Fun reading →



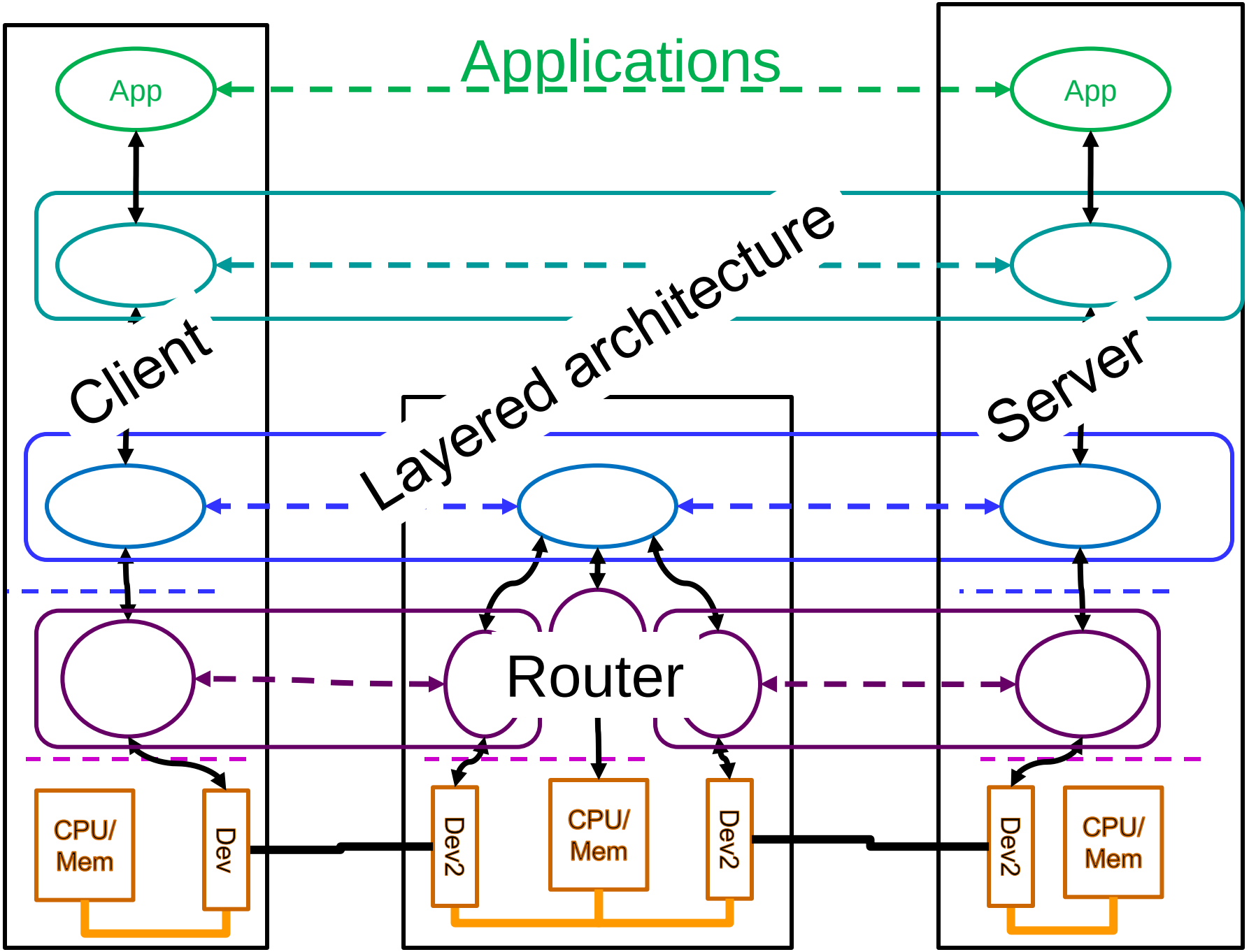
Architecture resources

- Networking
  - John Day, Patterns in Network Architecture
  - Content Centric (CCN, Xerox Parc, Jacobson)
  - Publish-Subscribe (PSIRP)
  - Lawyers: Zittrain, Choo
- Biology (many, but here's a few)
  - Gerhart and Kirschner (the big picture)
  - De Duve (if you want to quickly learn biochemistry)
  - Zimmer (if you want to learn about bacteria)
- Systems
  - Donella Meadows


WHAT THE
INTERNET
IS DOING TO
OUR BRAINS
THE
SHALLOWS
Nicholas Carr
AUTHOR OF THE BIG SWITCH


HALL
Patterns in
Network Architecture
A Return to Fundamentals
JOHN DAY


Sir, I'm going to have to ask you to leave the internet.
You're just too fucking stupid.

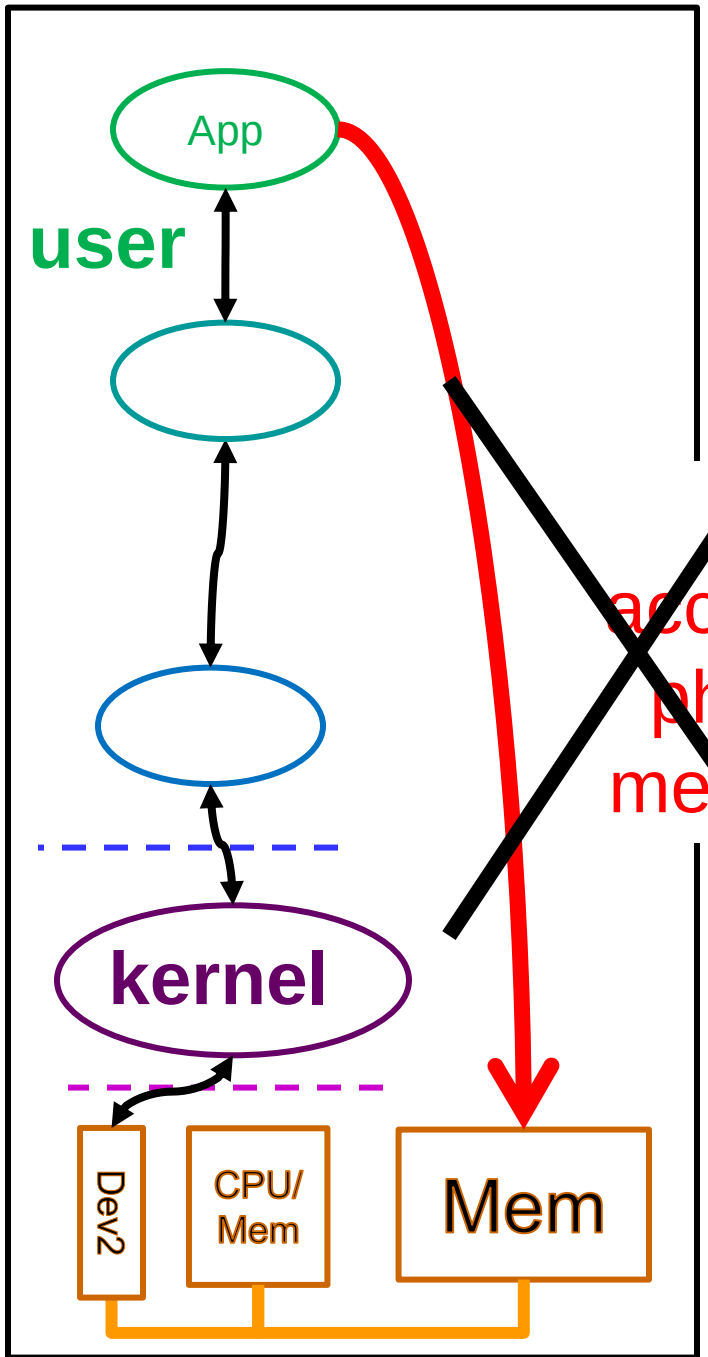

Applications
App
App
Client
Layered architecture
Server
Router
CPU/
Mem
Dev
Dev2
CPU/
Mem
Dev2
Dev2
CPU/
Mem

Naming and addressing

- Names needed to locate objects
- 2.5 ways to resolve a name
  1. Exhaustive search, table lookup
  2. Name gives hints
- Extra ½ is for indirection
- Address is just a name that involves locations

Operating systems

- OS allocates and shares diverse resources among diverse applications
- Clearly separate (disaster otherwise)
  - Application name space
  - Logical (virtual) name/address space
  - Physical (name/) address space
- Name resolution within applications
- Name/address translation across layers



In operating systems:
Don't cross layers

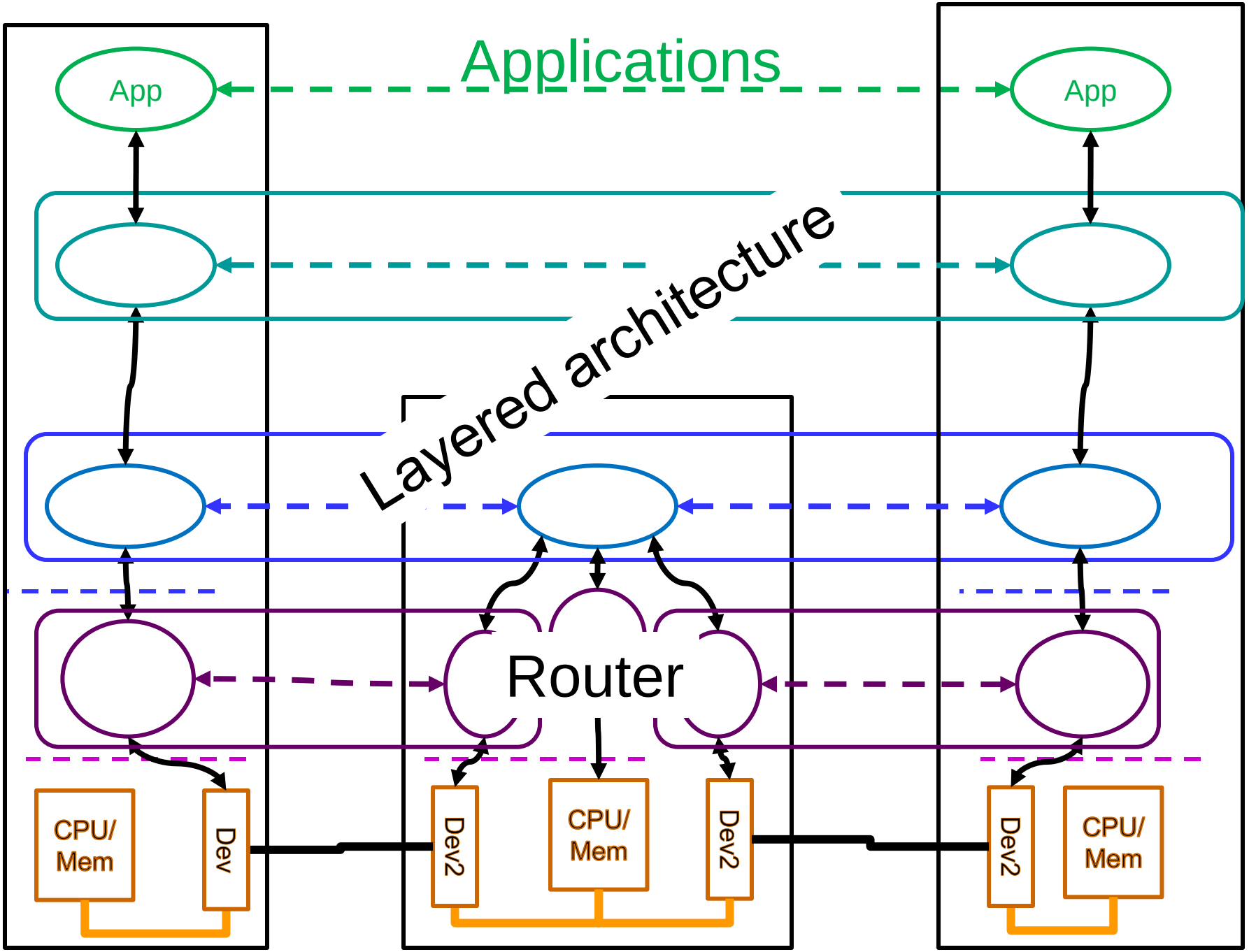
Direct access to physical memory?

Benefits of stricter layering

"Black box" effects of stricter layering

- Portability of applications
- Security of physical address space
- Robustness to application crashes
- Scalability of virtual/real addressing

- Optimization/control by duality?


Applications
App
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Layered architecture
Router
CPU/
Mem
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Dev2
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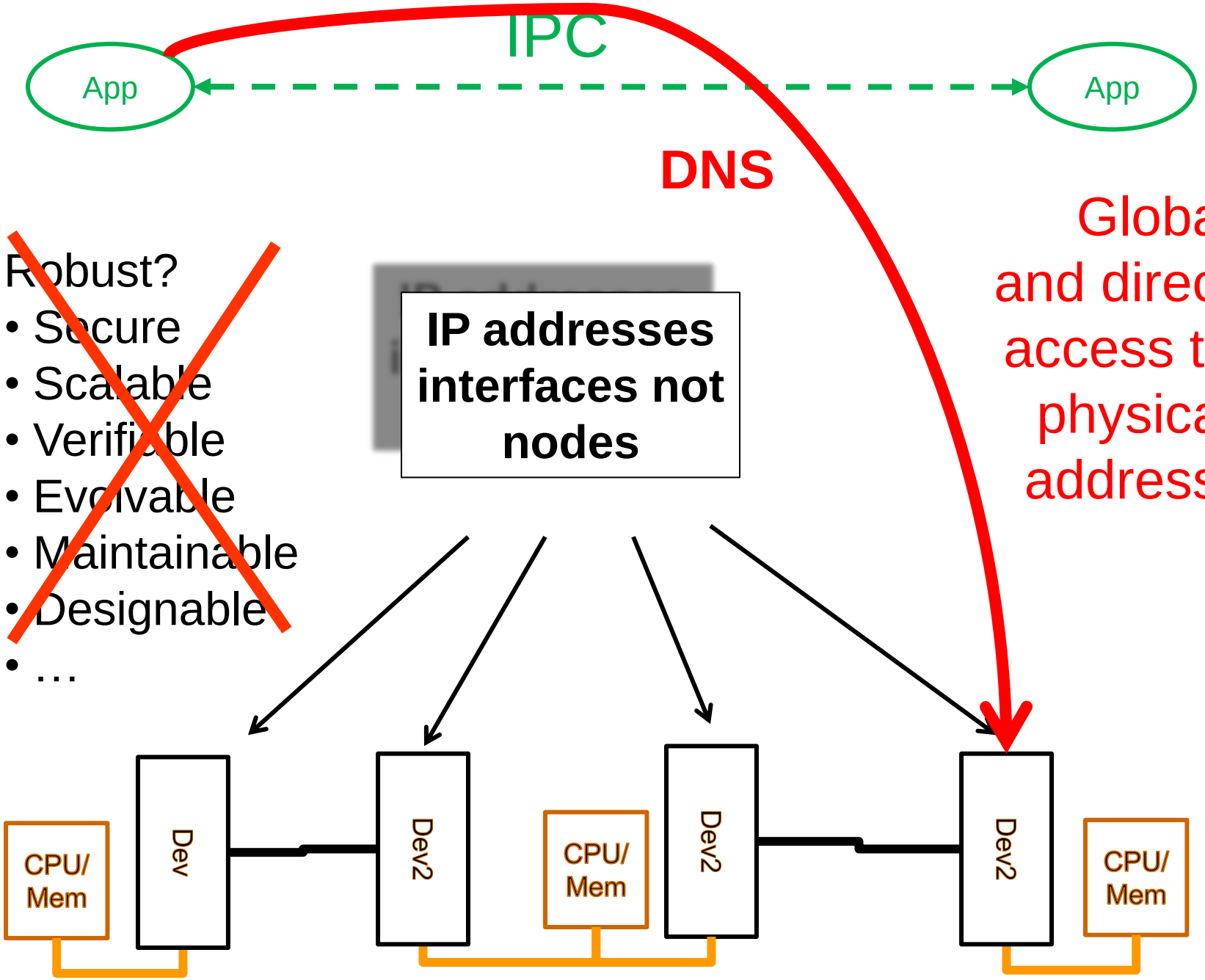
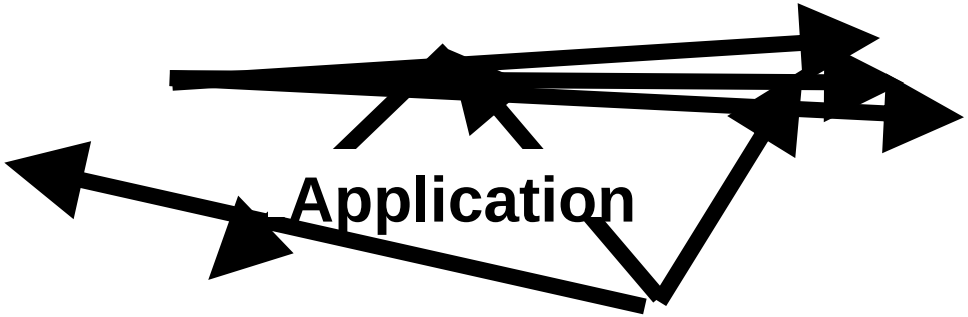
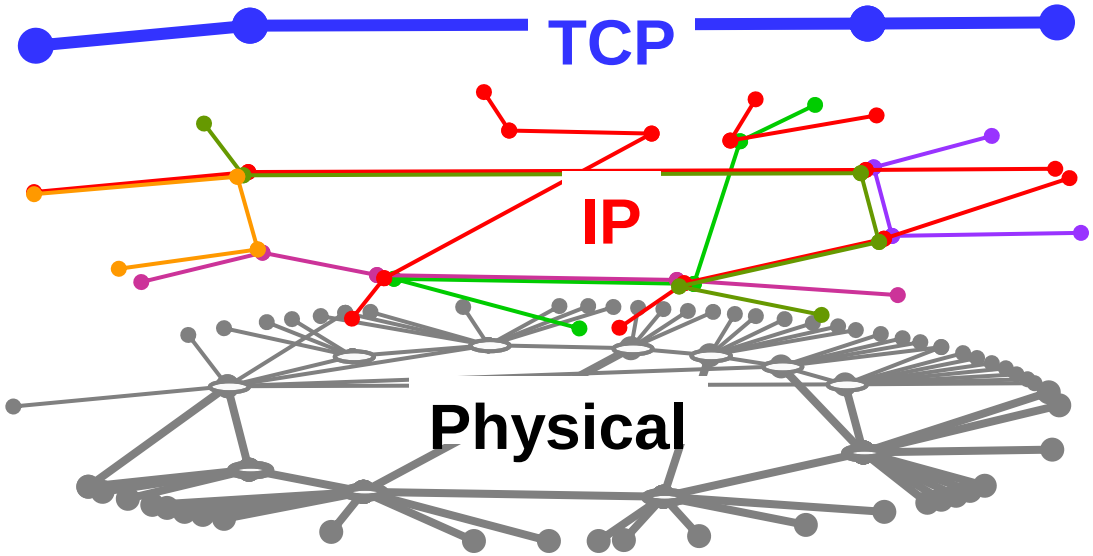
Mem
Dev2
Dev2
CPU/
Mem


IPC
App
App
DNS
Global and direct access to physical address!
Robust?
• Secure
• Scalable
• Verifiable
• Evolvable
• Maintainable
• Designable
• …
IP addresses interfaces not nodes
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

Naming and addressing need to be
- resolved within layer
- translated between layers
- not exposed outside of layer

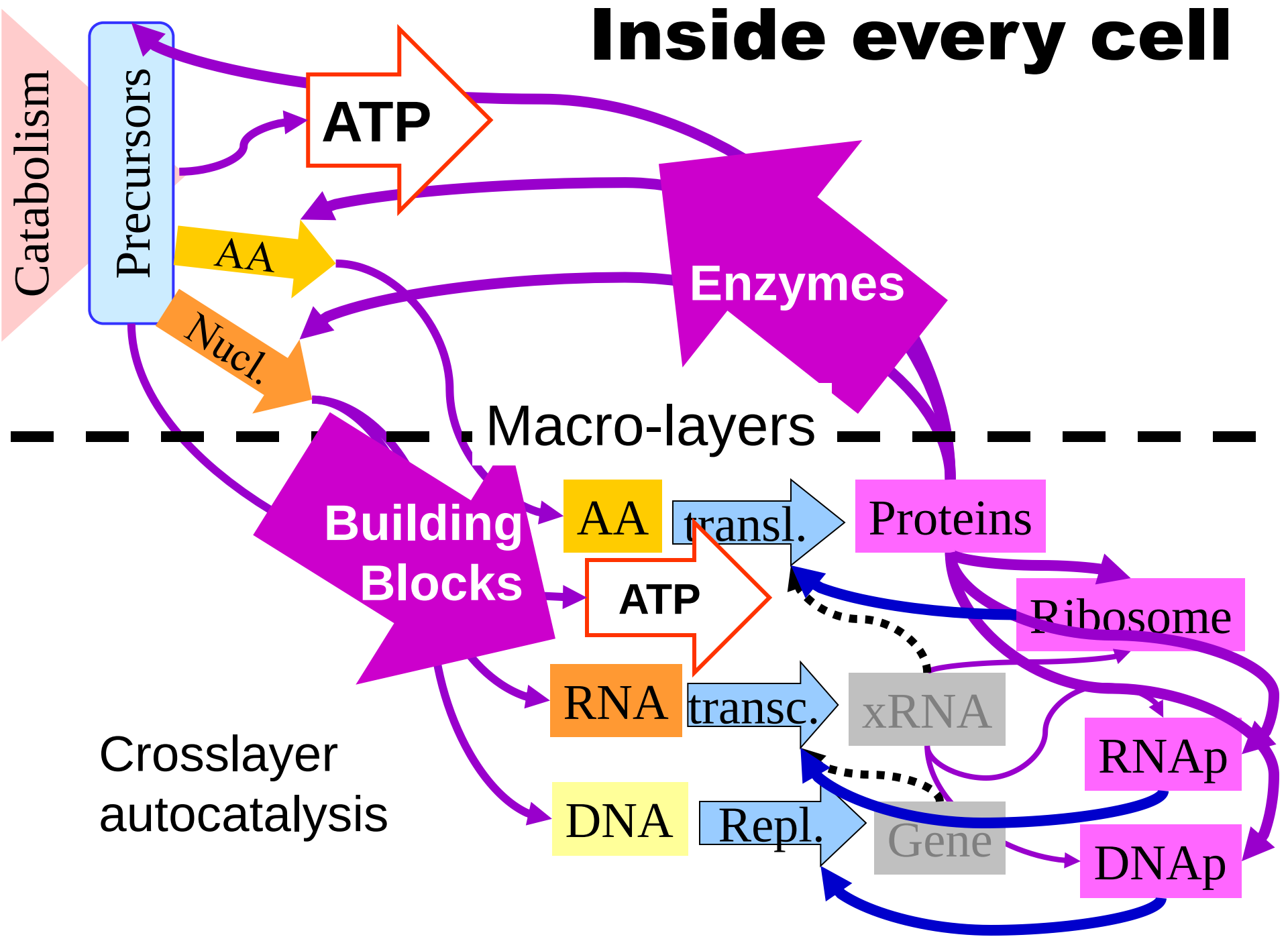
Related issues
- DNS
- NATS
- Firewalls
- Multihoming
- Mobility
- Routing table size
- Overlays
- …





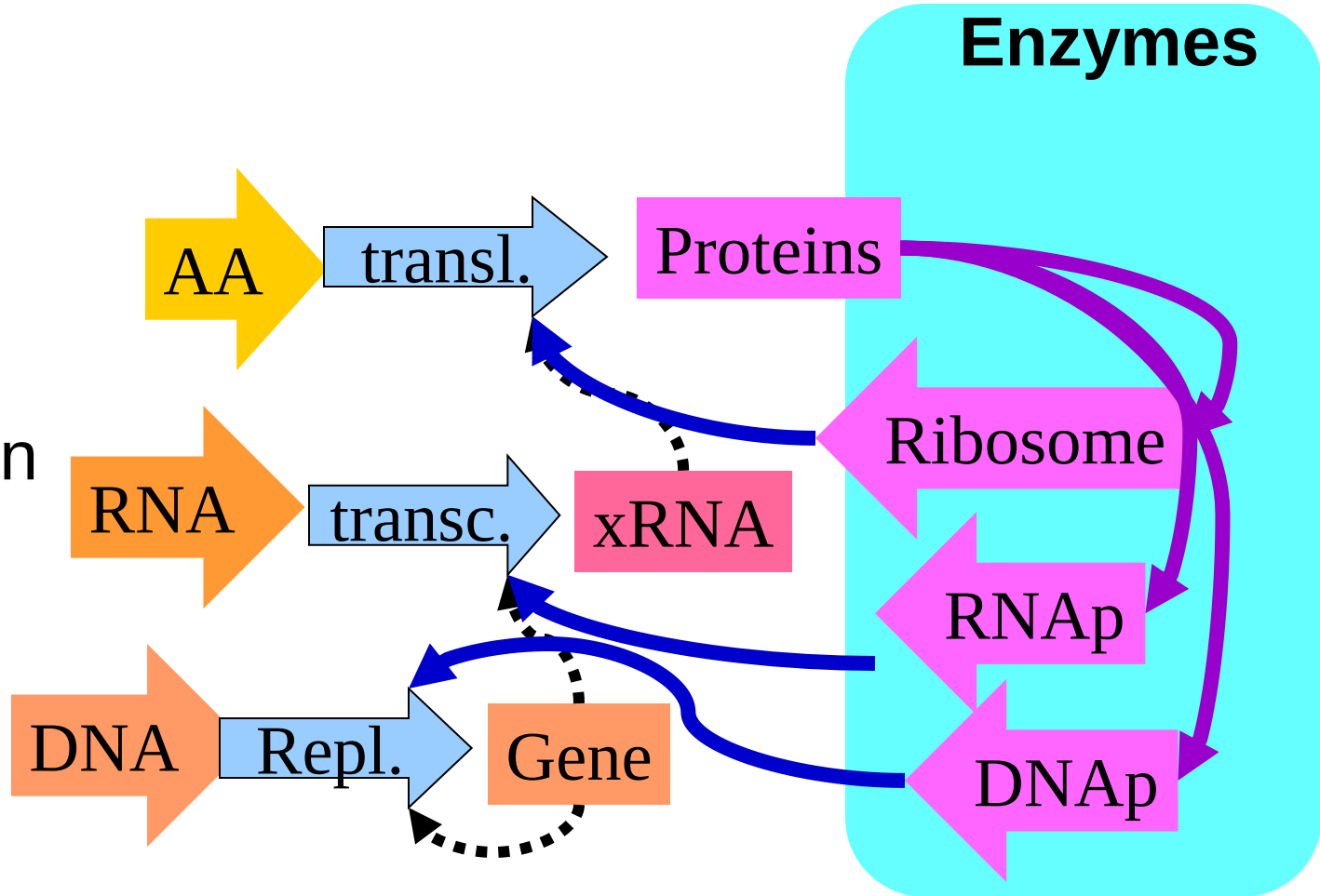
Clean slate layering?

- Two “macrolayers” with a new, higher “waist”
  - Upper: Managing content, function, naming
  - Lower: Managing physical resources, addressing
- Lower layers: map to physical addresses (PNA)
  - Recursive “microlayers” of control and management
  - Different scopes (more global and lumped to more local and detailed)
  - No global addresses, hide details, addresses
- Cleaner role of optimization and control?
- Integration with naming and addressing
- Align robustness and security


Inside every cell
Catabolism
Precursors
ATP
AA
Nucl.
Enzymes
Macro-layers
Building Blocks
AA
transl.
Proteins
ATP
Ribosome
RNA
transc.
xRNA
RNAp
DNA
Repl.
Gene
DNAp
Crosslayer autocatalysis

Lower layer autocatalysis
Macromolecules making …

Three lower layers? Yes:
- Translation
- Transcription
- Replication



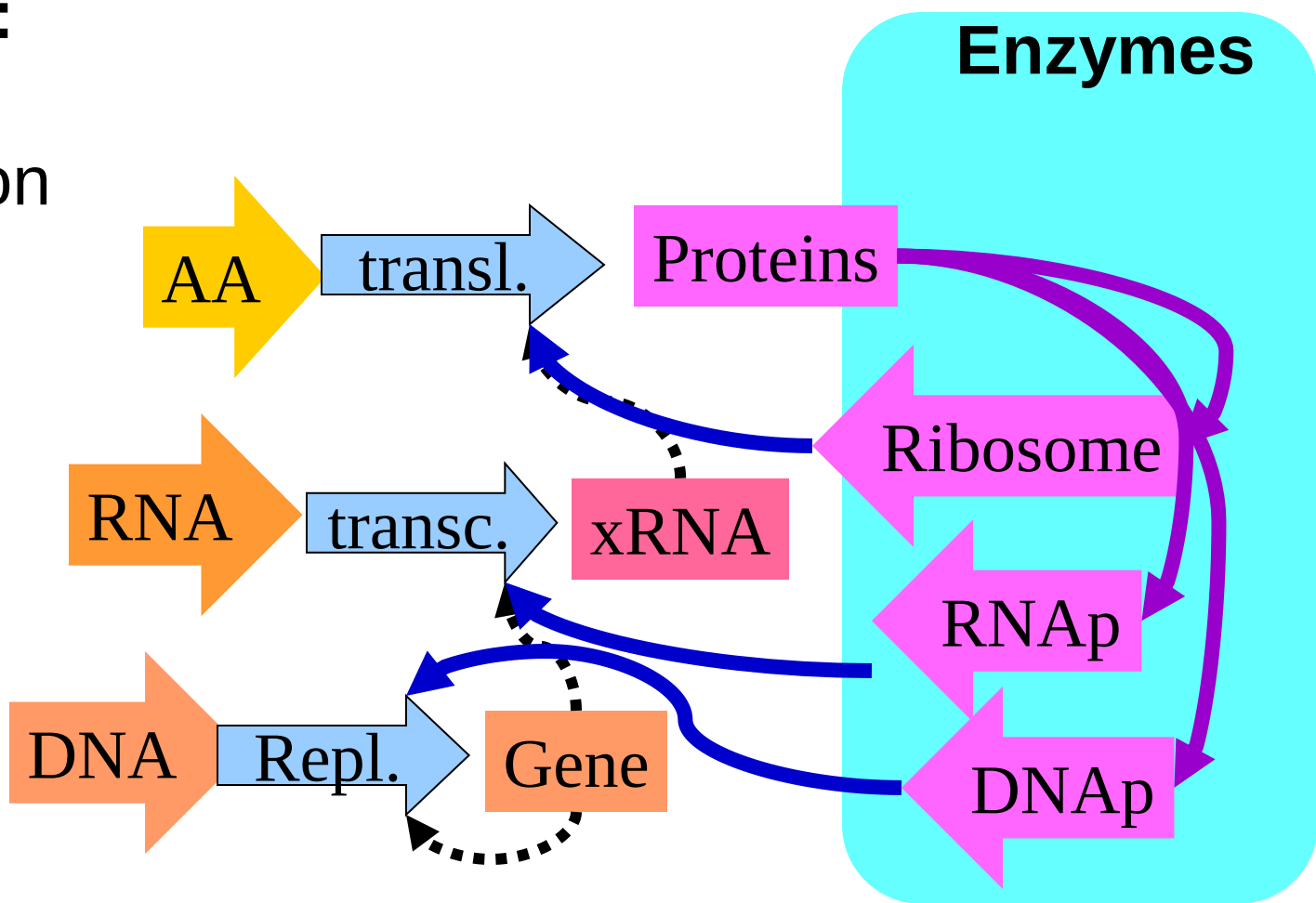
Autocatalytic within lower layers

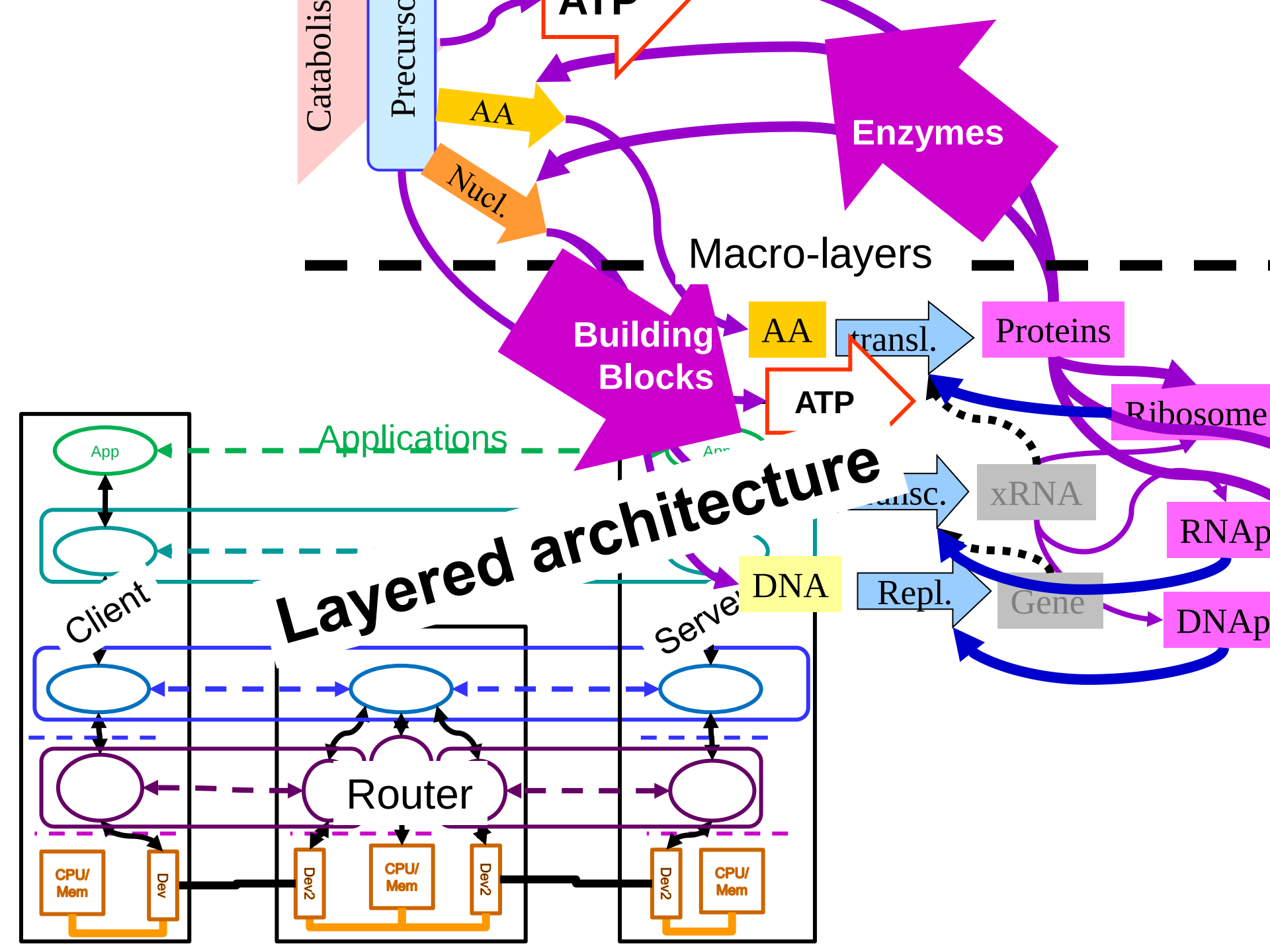
- Collectively self-replicating
- Ribosomes make ribosomes, etc

Three lower layers? Yes:

- Translation
- Transcription
- Replication

Naturally recursive

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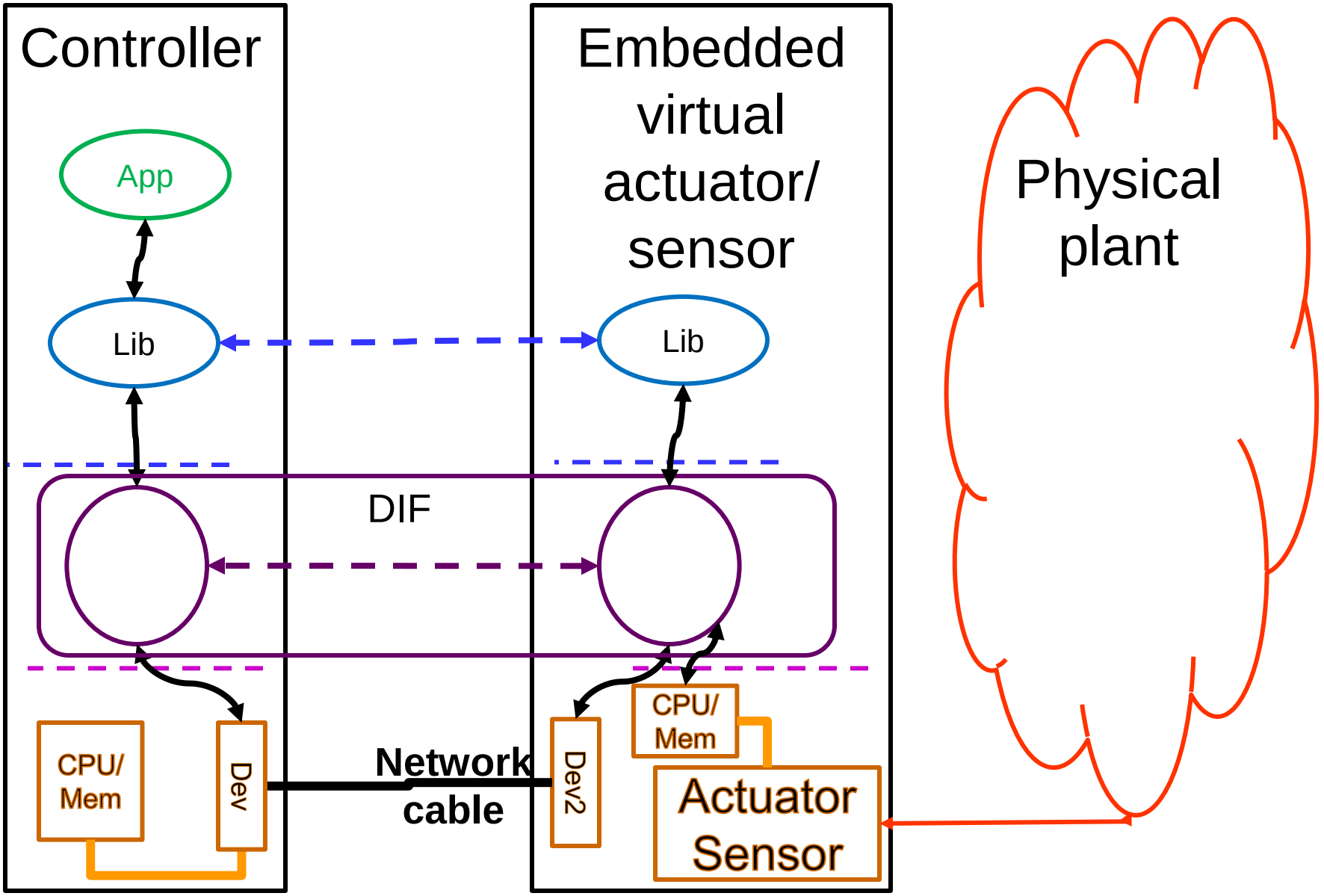
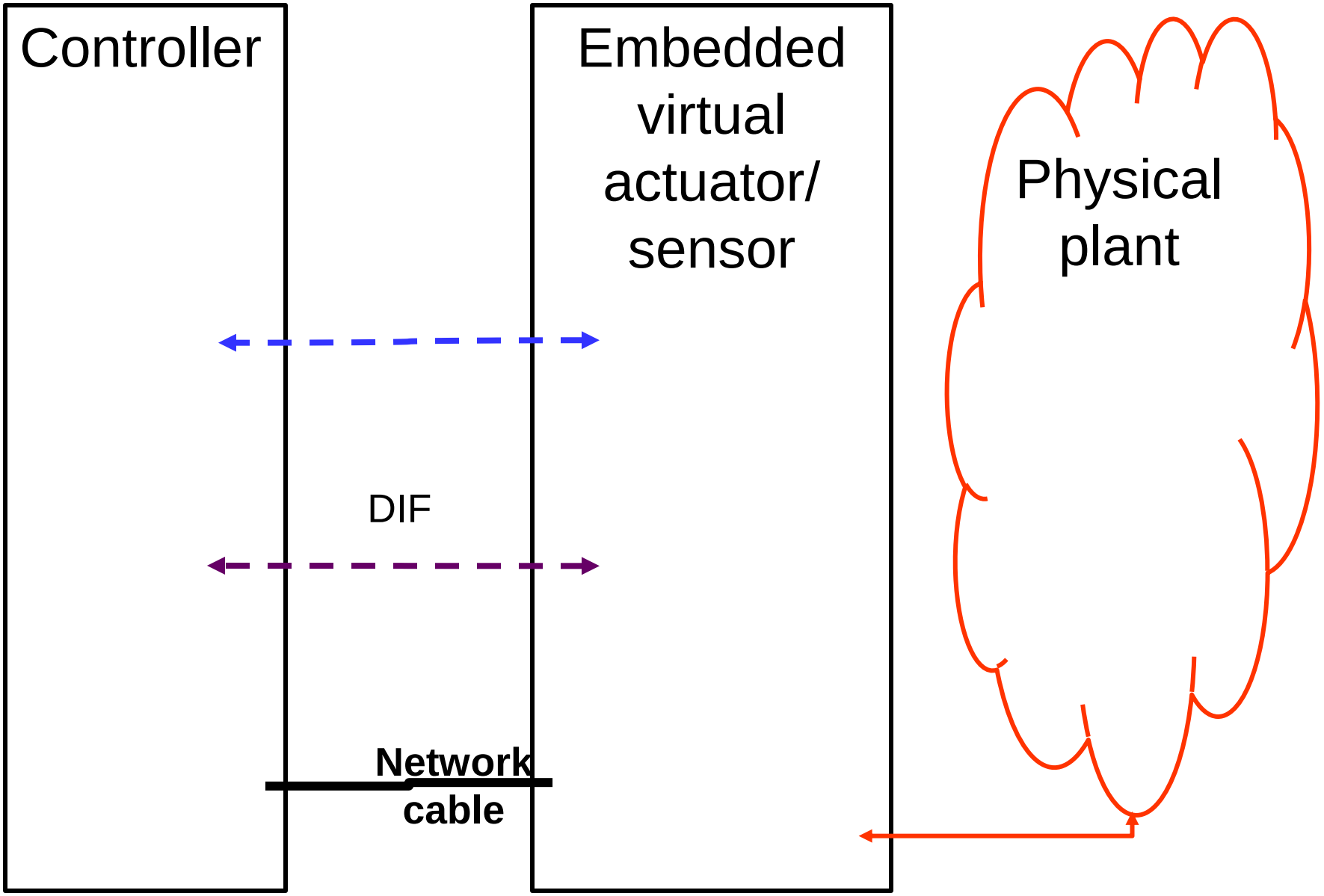
Gene
DNAp
Layered architecture
App
Client
Server
Router
CPU/ Mem
Dev
Dev2
CPU/ Mem
Dev2
Dev2
CPU/ Mem

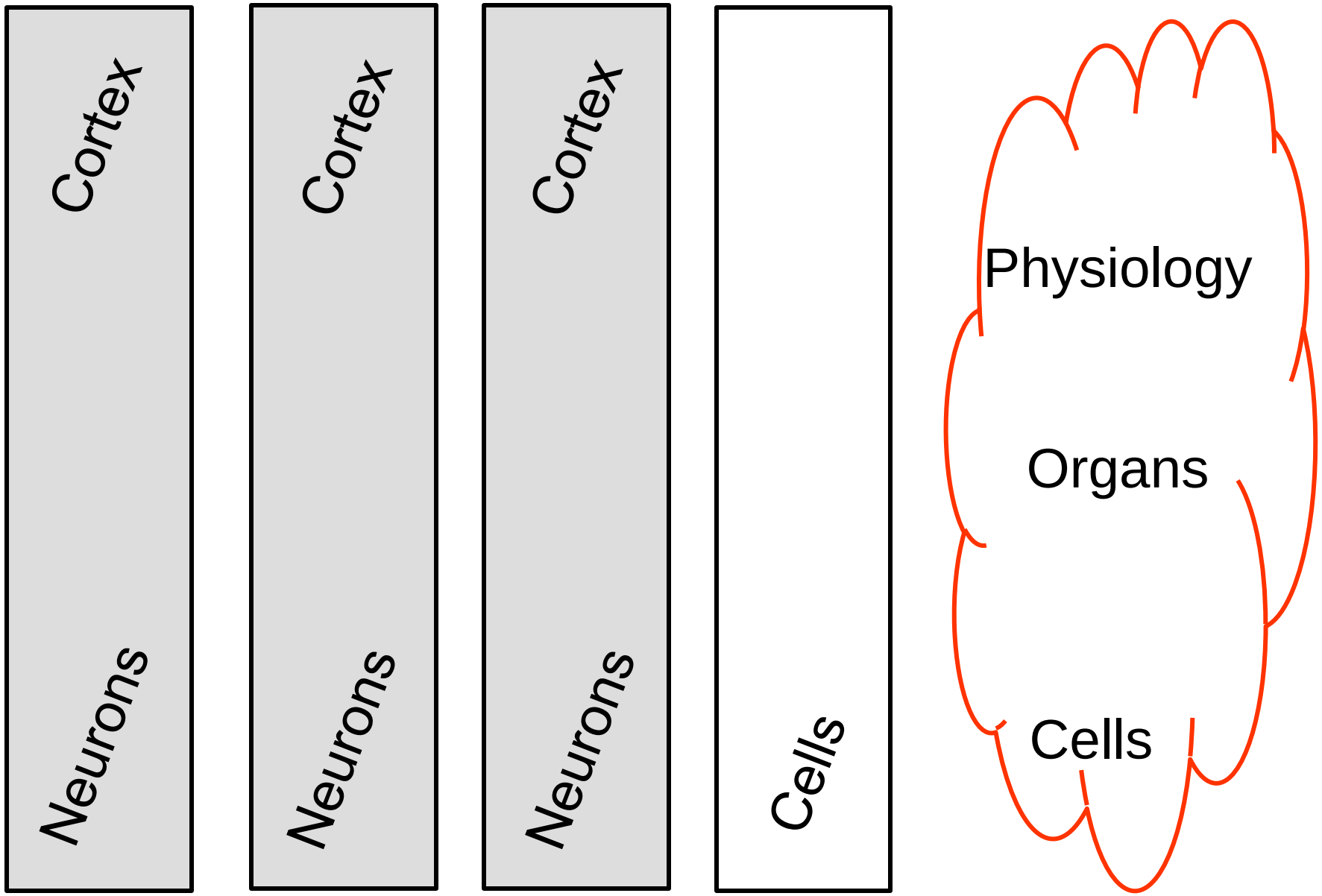
Networked embedded

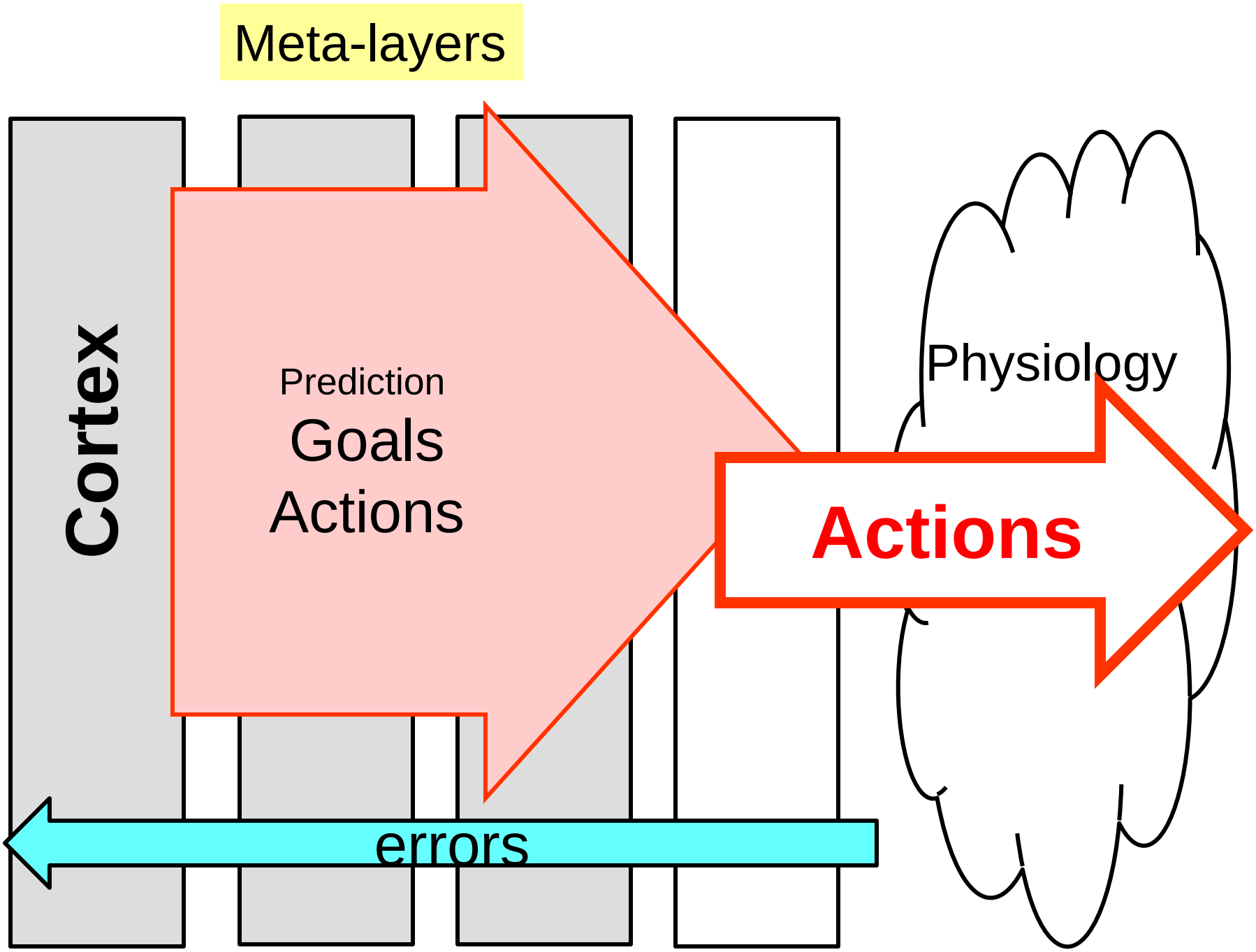


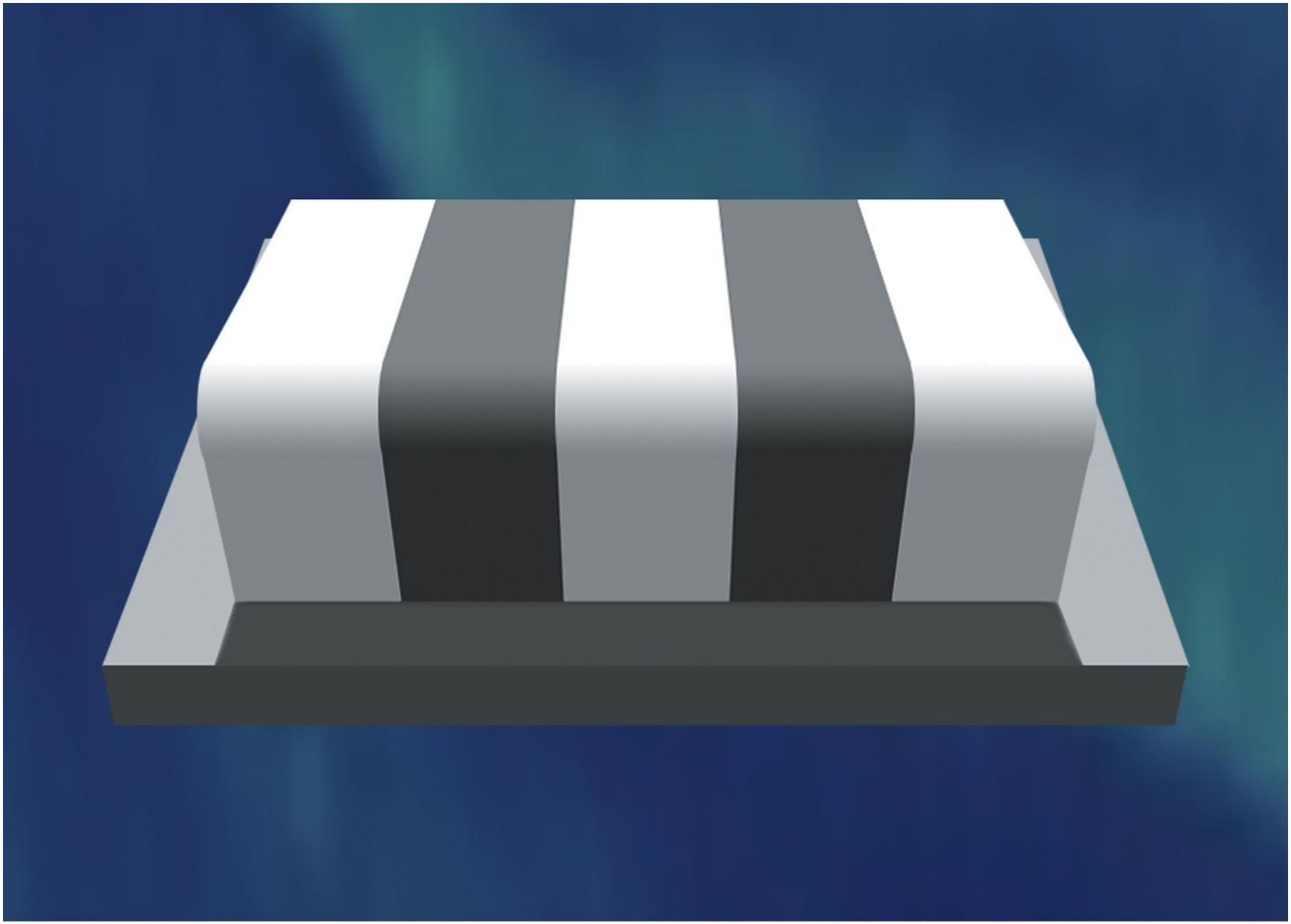
Meta-layering of cyber-phys control



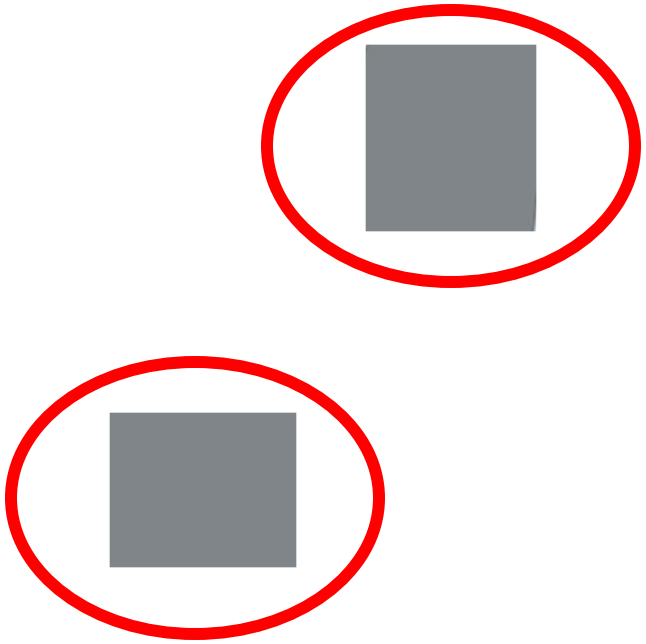
Meta-layers


Cortex
Neurons
Cortex
Neurons
Cortex
Neurons
Cells
Physiology
Organs
Cells

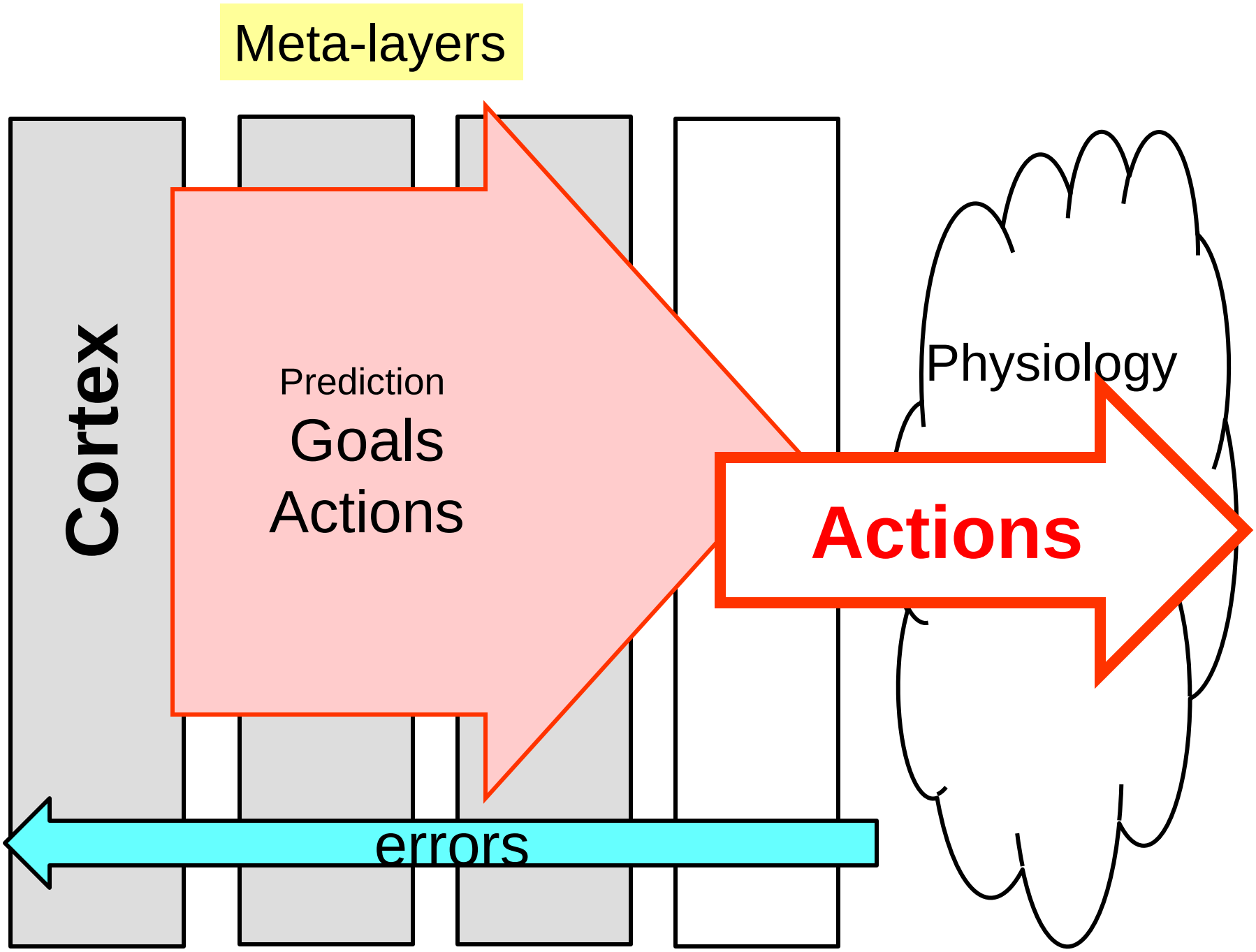

Meta-layers
Cortex
Prediction
Goals
Actions
Physiology
Actions
errors

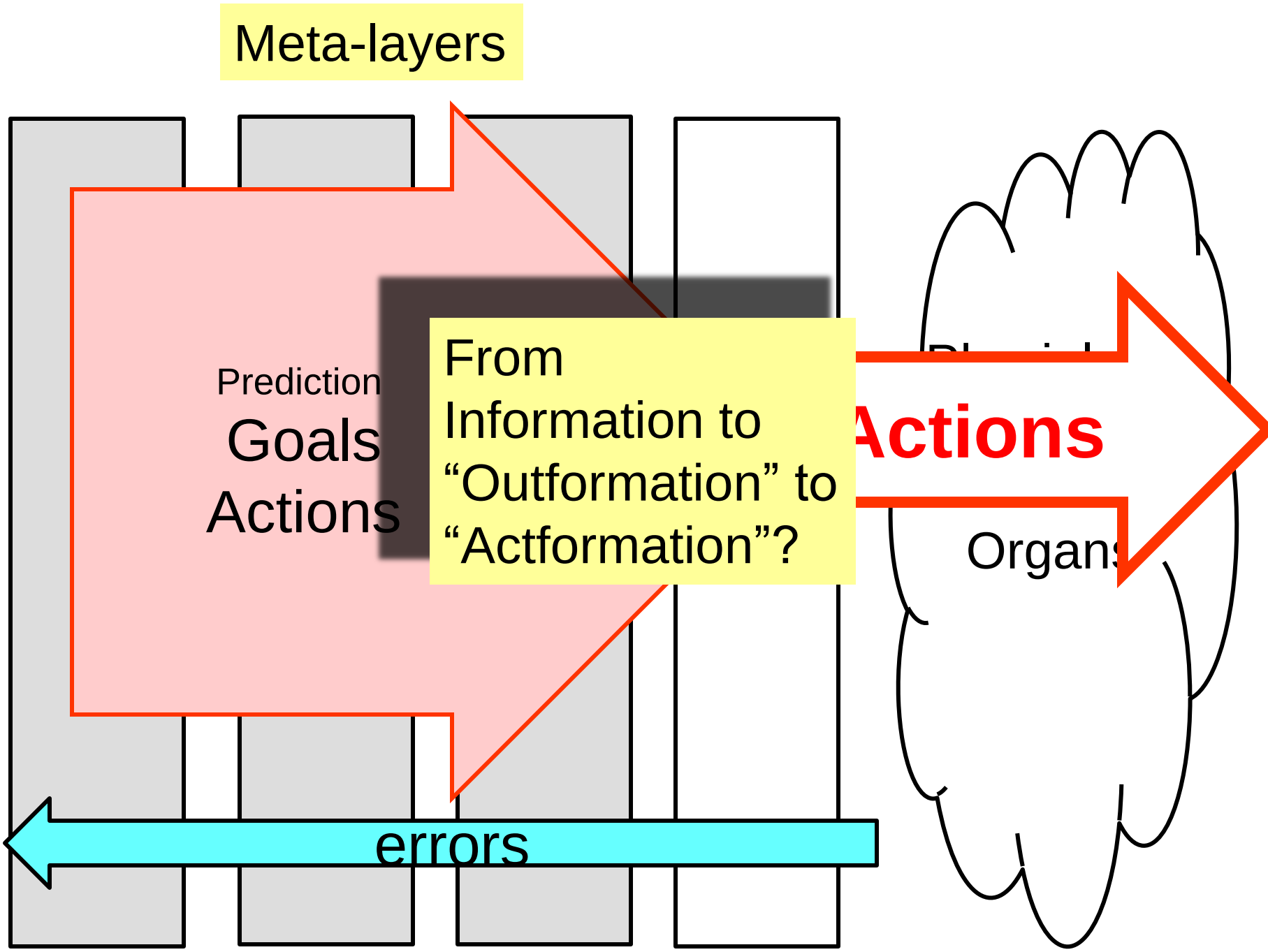


Dale Purves



In the brain:
Don’t cross layers


Meta-layers
Cortex
Prediction
Goals
Actions
Physiology
Actions
errors


Meta-layers
Prediction
Goals
Actions
From
Information to
“Outformation” to
“Actformation”?
Actions
Organs
errors

Meta-layers

Cortex

Cortex

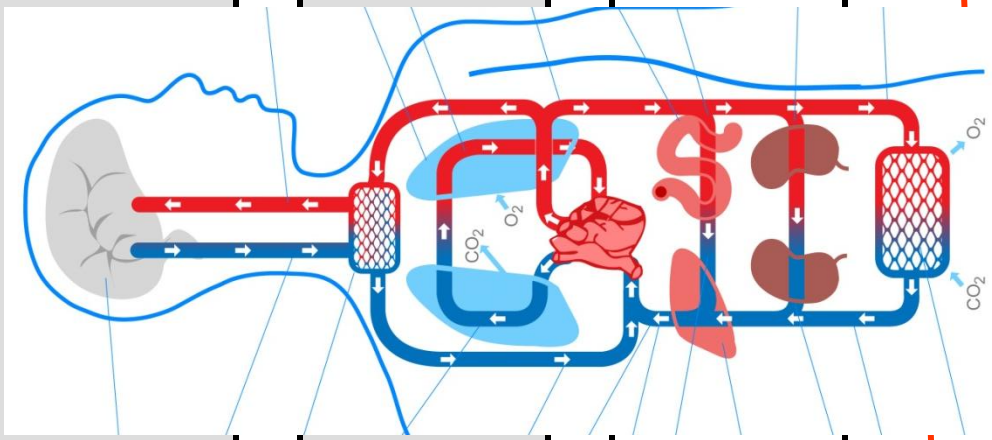
Cortex

Neurons

Neurons

Neurons

Cells



Physiology

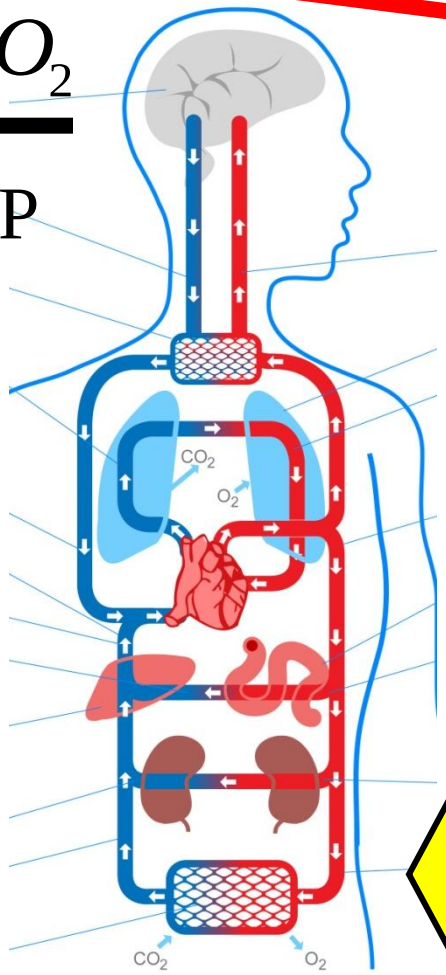
Organs

Cells

Minimize resulting fluctuations in

SpO_2

BP



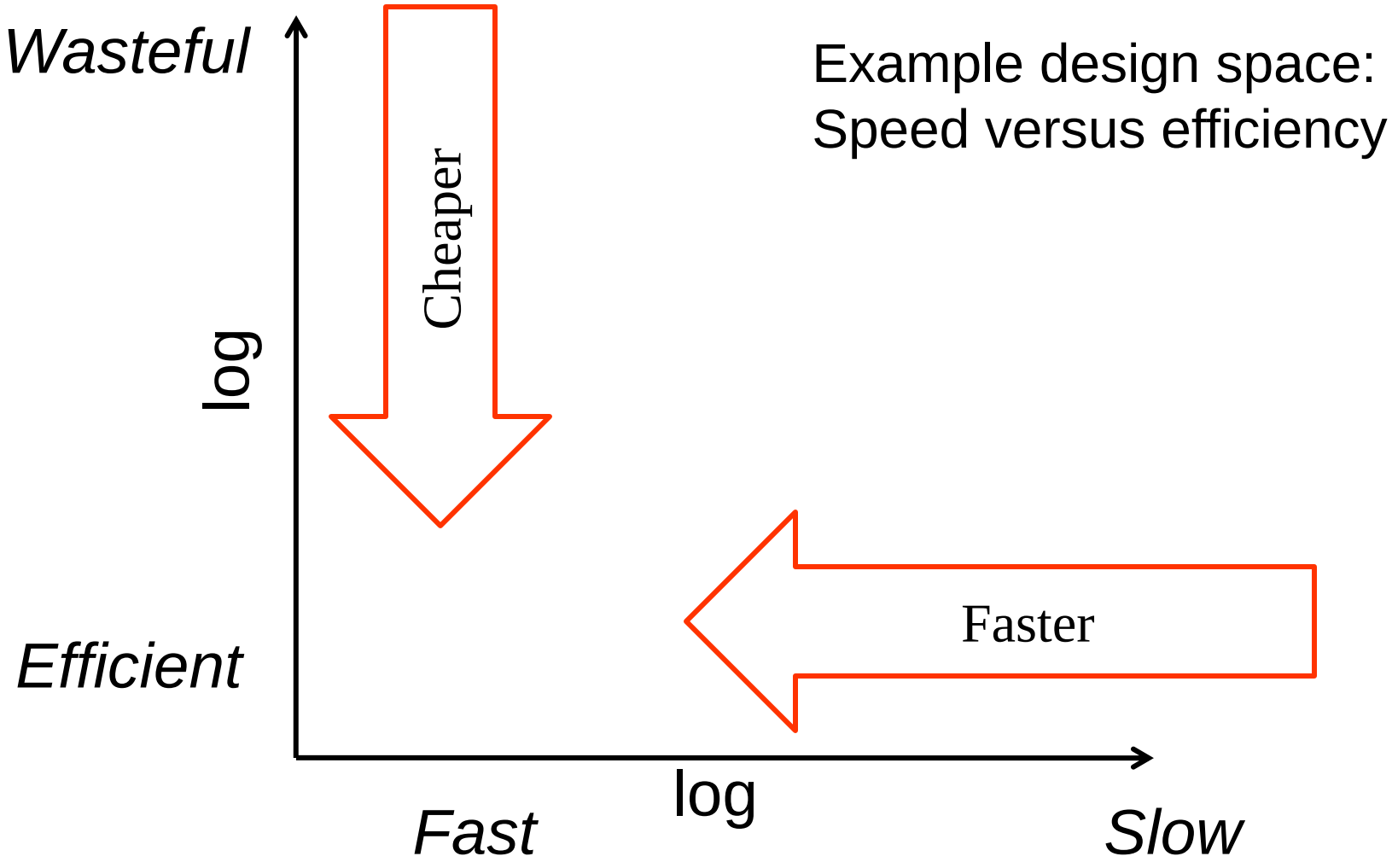
(Evolution + physiology)

Maximize allowable fluctuations in

watts

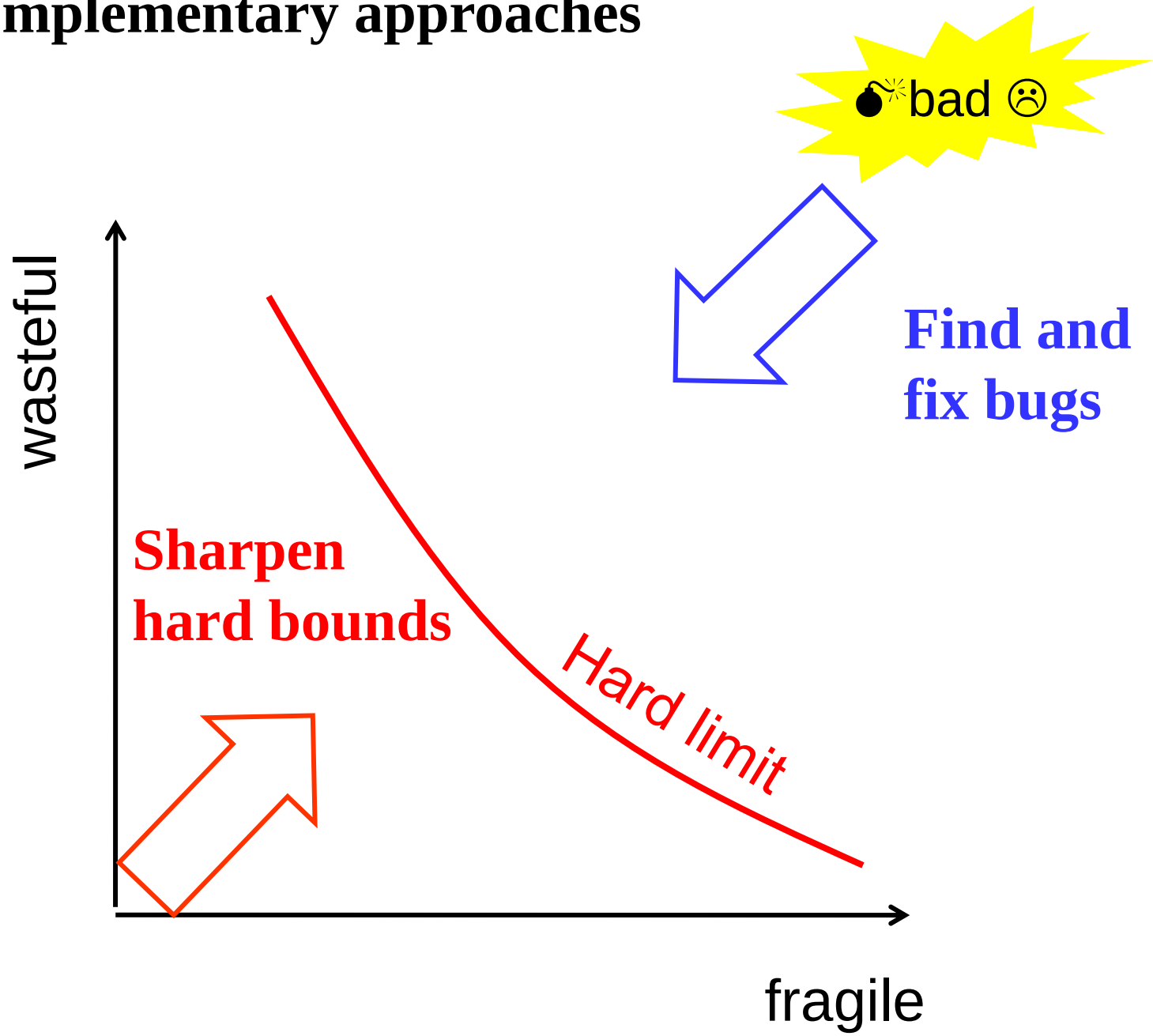
Simple starting point.

Design tradeoffs



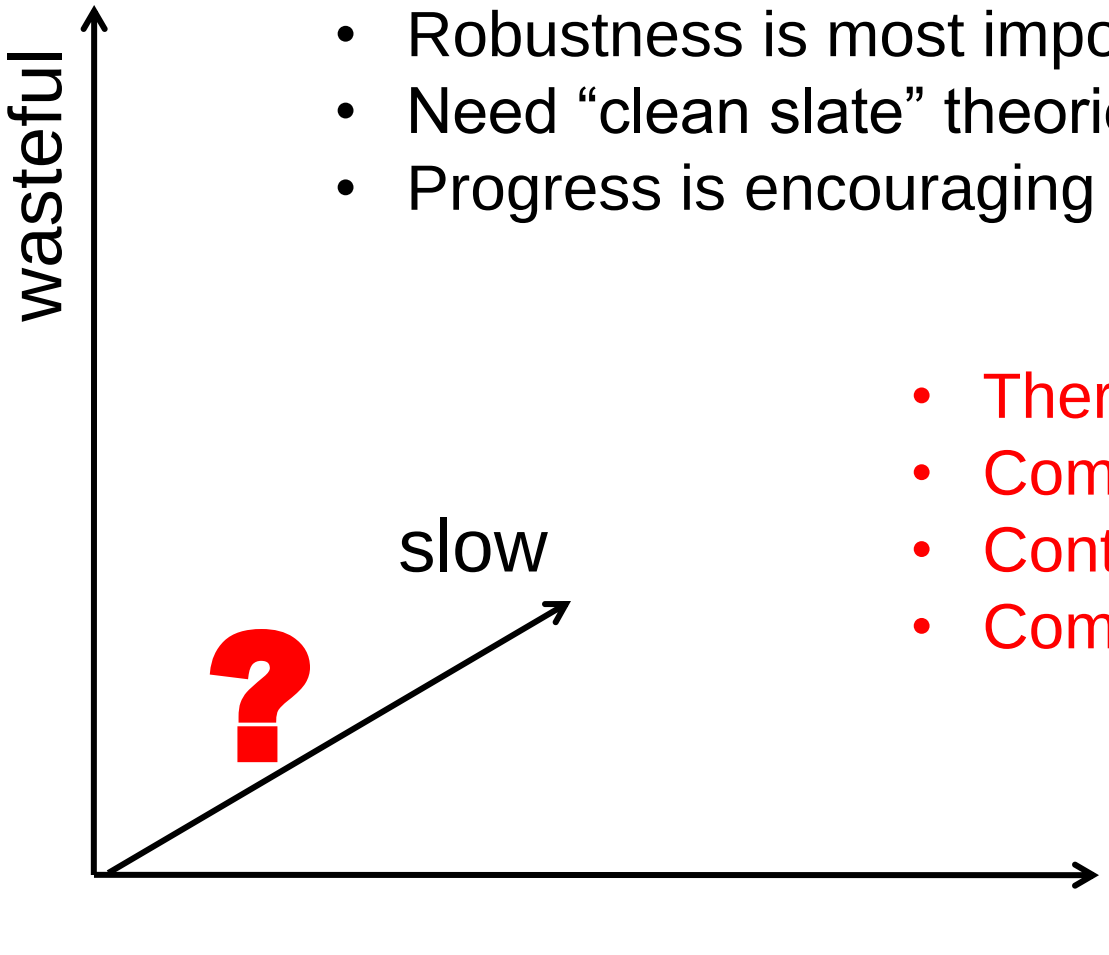
Example design space:
Speed versus efficiency

Complementary approaches



Standard theories are severely limited

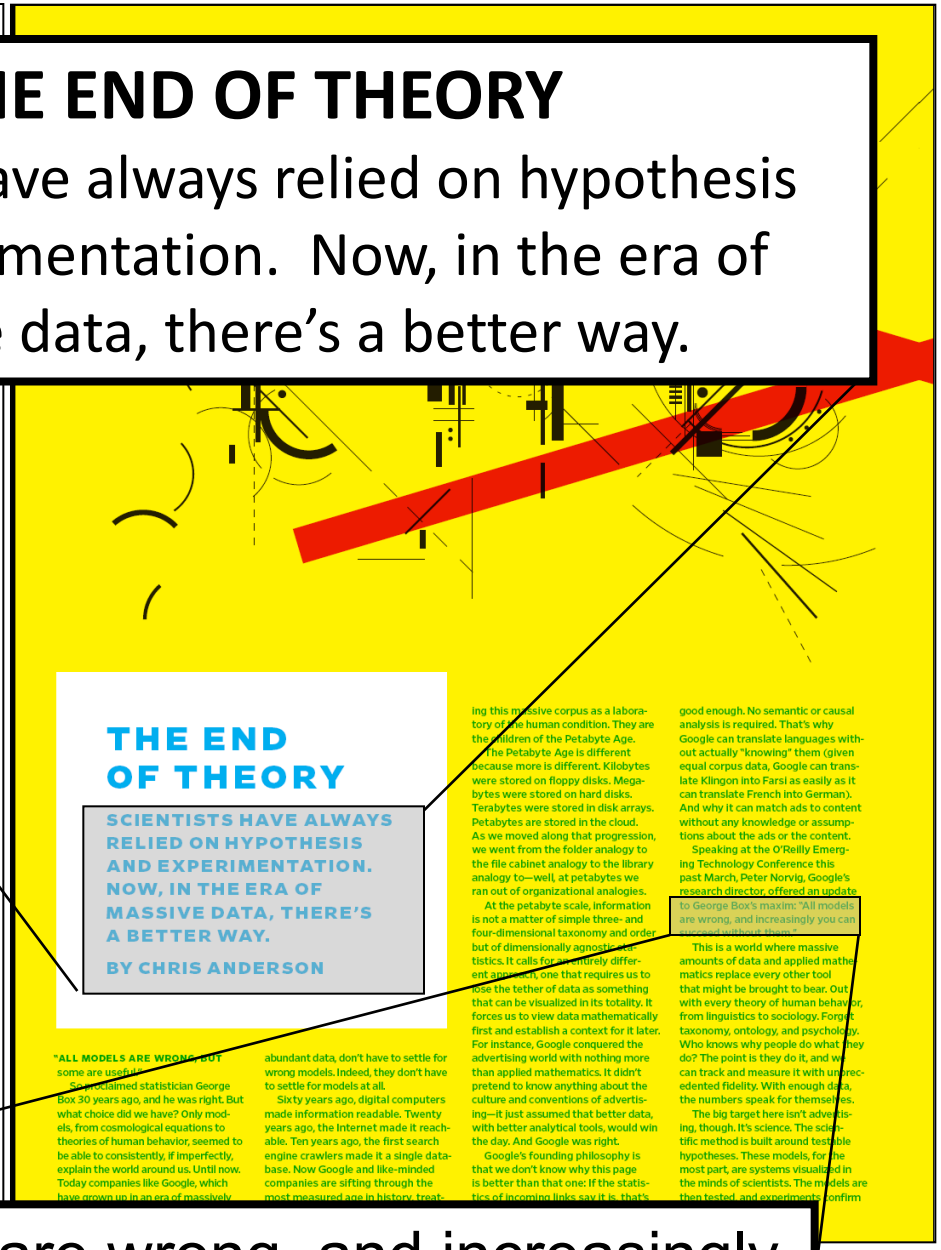
- Each focuses on few dimensions
- Important tradeoffs are ***across*** these dimensions
- Speed vs efficiency vs robustness vs …
- Robustness is most important for complexity
- Need “clean slate” theories
- Progress is encouraging



- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing)

THE END OF THEORY

Scientists have always relied on hypothesis and experimentation. Now, in the era of massive data, there's a better way.



THE END OF THEORY

SCIENTISTS HAVE ALWAYS RELIED ON HYPOTHESIS AND EXPERIMENTATION. NOW, IN THE ERA OF MASSIVE DATA, THERE'S A BETTER WAY.

BY CHRIS ANDERSON

"ALL MODELS ARE WRONG, BUT some are useful."

So proclaimed statistician George Box 30 years ago, and he was right. But what choice did we have? Only models, from cosmological equations to theories of human behavior, seemed to be able to consistently, if imperfectly, explain the world around us. Until now. Today companies like Google, which have grown up in an era of massively abundant data, don't have to settle for wrong models. Indeed, they don't have to settle for models at all.

Sixty years ago, digital computers made information readable. Twenty years ago, the Internet made it reachable. Ten years ago, the first search engine crawlers made it a single database. Now Google and like-minded companies are sifting through the most measured age in history, treating this massive corpus as a laboratory of the human condition. They are the children of the Petabyte Age.

The Petabyte Age is different because more is different. Kilobytes were stored on floppy disks. Megabytes were stored on hard disks. Terabytes were stored in disk arrays. Petabytes are stored in the cloud. As we moved along that progression, we went from the folder analogy to the file cabinet analogy to the library analogy to—well, at petabytes we ran out of organizational analogies.

At the petabyte scale, information is not a matter of simple three- and four-dimensional taxonomy and order but of dimensionally agnostic statistics. It calls for an entirely different approach, one that requires us to lose the tether of data as something that can be visualized in its totality. It forces us to view data mathematically first and establish a context for it later. For instance, Google conquered the advertising world with nothing more than applied mathematics. It didn't pretend to know anything about the culture and conventions of advertising—it just assumed that better data, with better analytical tools, would win the day. And Google was right.

Google's founding philosophy is that we don't know why this page is better than that one: If the statistics of incoming links say it is, that's good enough. No semantic or causal analysis is required. That's why Google can translate languages without actually "knowing" them (given equal corpus data, Google can translate Klingon into Farsi as easily as it can translate French into German). And why it can match ads to content without any knowledge or assumptions about the ads or the content.

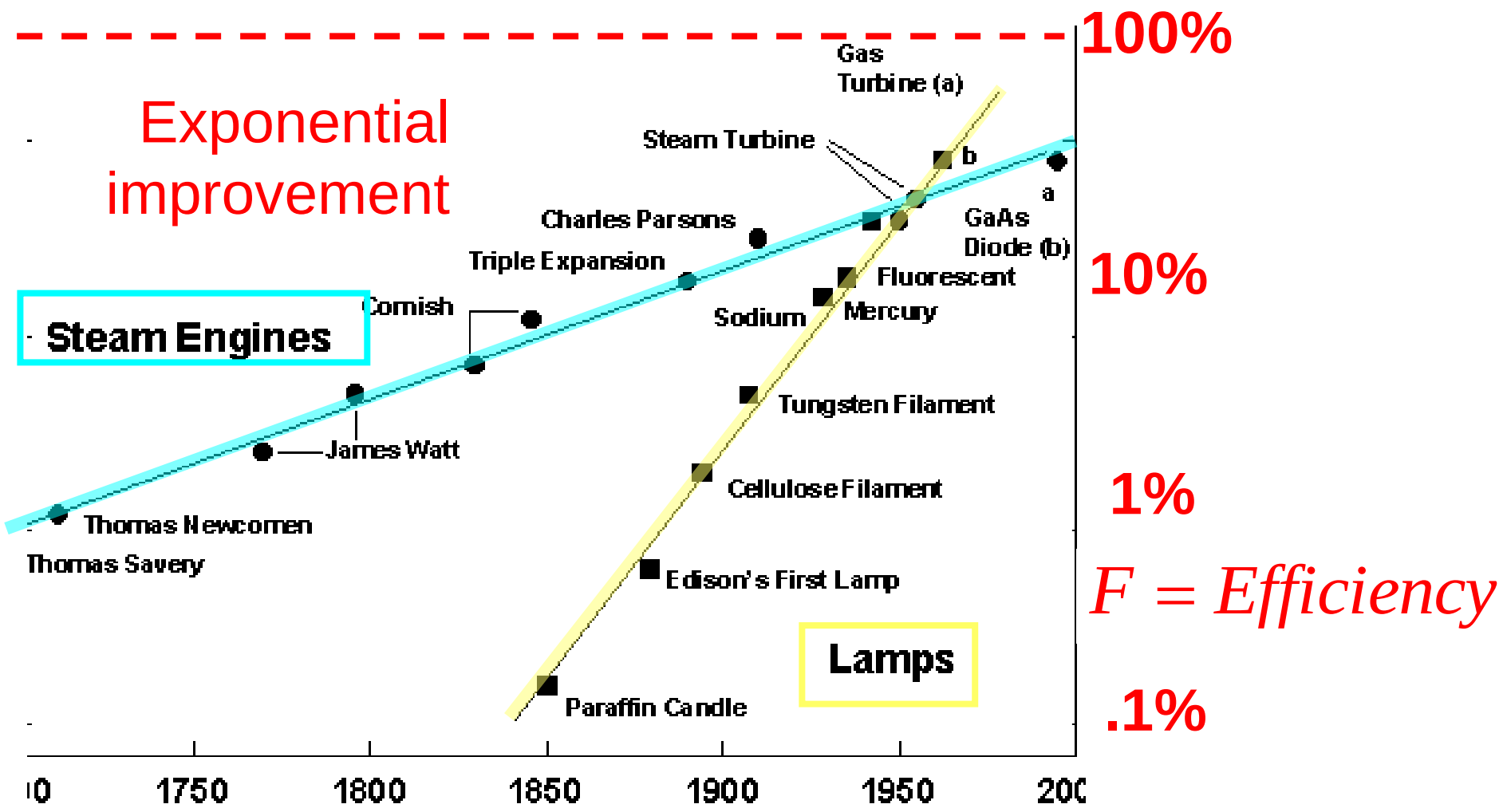
Speaking at the O'Reilly Emerging Technology Conference this past March, Peter Norvig, Google's research director, offered an update to George Box's maxim: "All models are wrong, and increasingly you can succeed without them."

This is a world where massive amounts of data and applied mathematics replace every other tool that might be brought to bear. Out with every theory of human behavior, from linguistics to sociology. Forget taxonomy, ontology, and psychology. Who knows why people do what they do? The point is they do it, and we can track and measure it with unprecedented fidelity. With enough data, the numbers speak for themselves.

The big target here isn't advertising, though. It's science. The scientific method is built around testable hypotheses. These models, for the most part, are systems visualized in the minds of scientists. The models are then tested, and experiments confirm

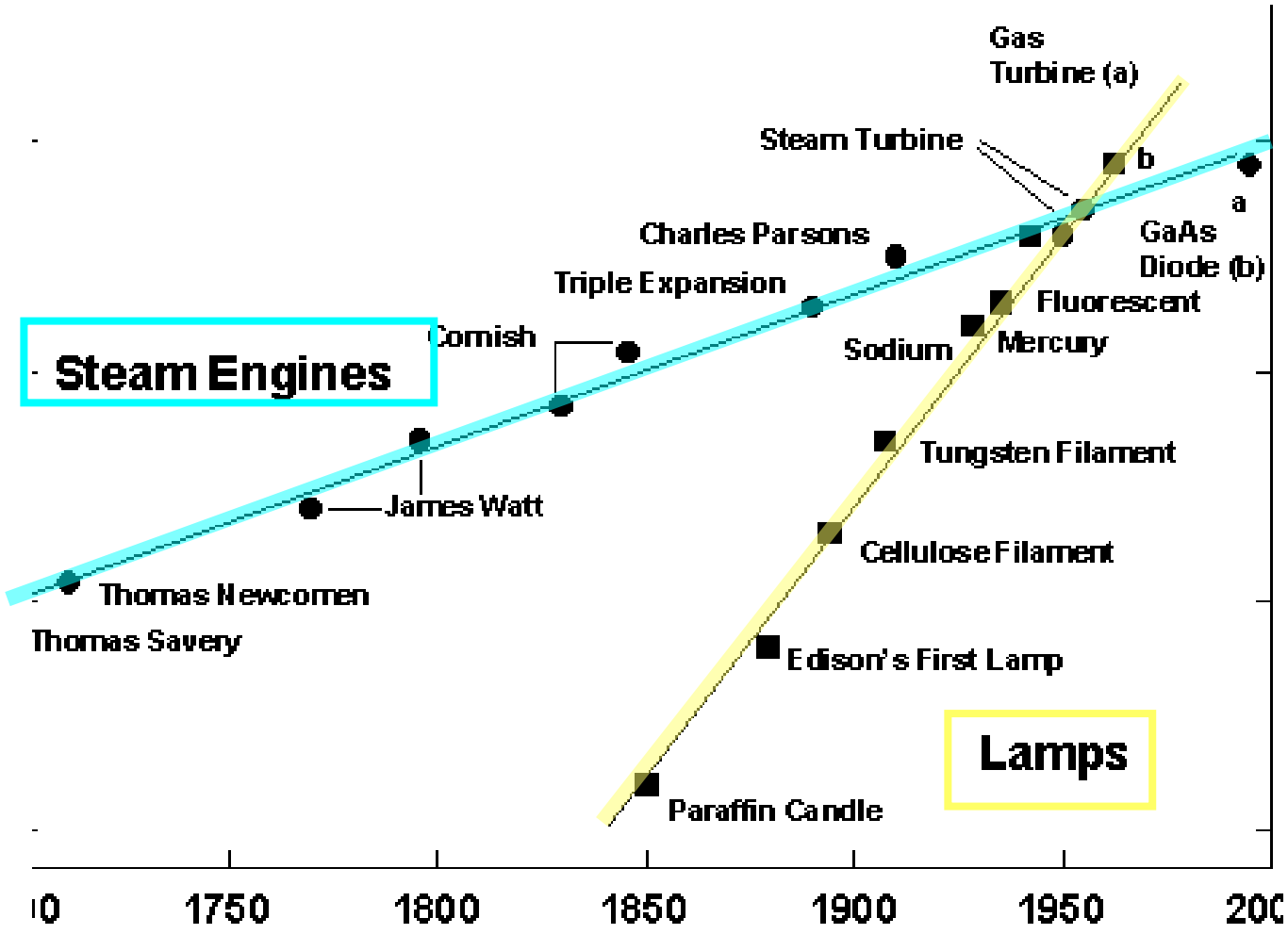
"All models are wrong, and increasingly you can succeed without them."

When will steam engines be 200% efficient?



http://phe.rockefeller.edu/Daedalus/Elektron/

When will steam engines be 200% efficient?



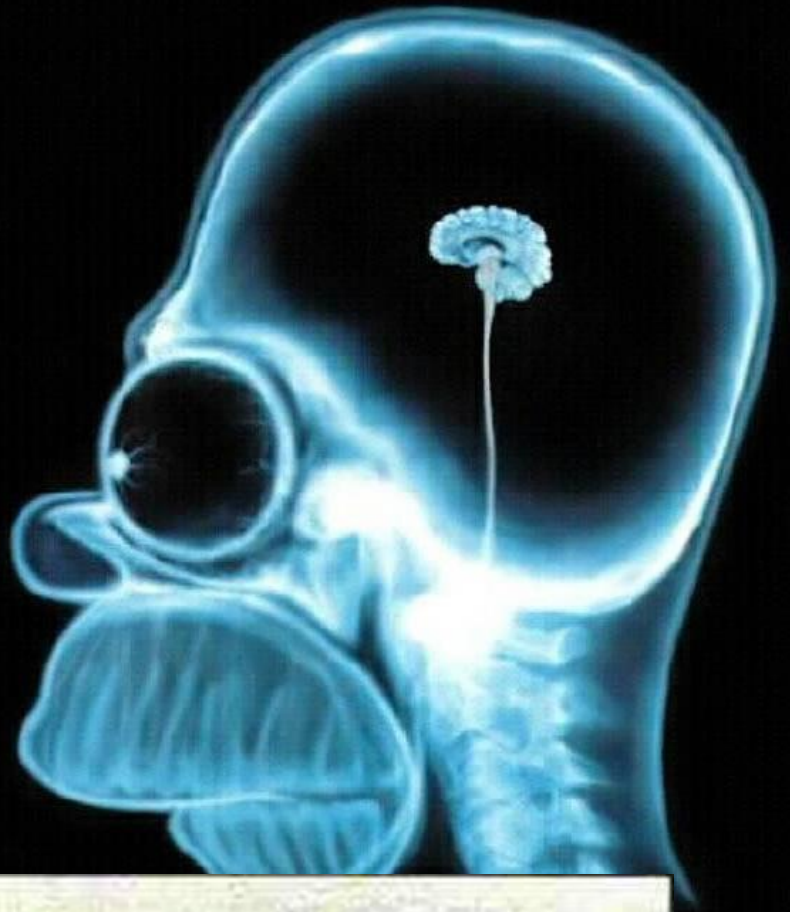
$$\frac{F}{1-F}$$

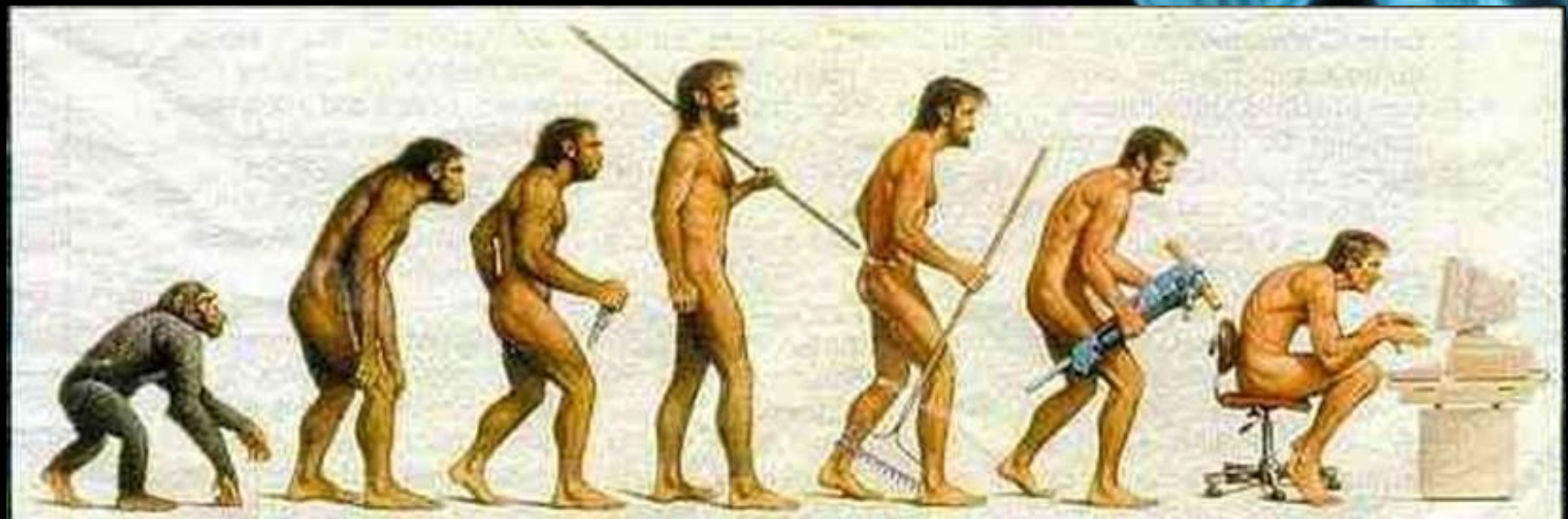
$F = Efficiency$

http://phe.rockefeller.edu/Daedalus/Elektron/

New words

- **Peta-philia**: Perverse love of data and computation
- **Peta-fop**: Someone who profits from peta-philia
- **Exa-duhs**: Loss of clue from excessive peta-philia





1 TERABYTE

A $200 HARD DRIVE THAT HOLDS 260,000 SONGS

20 TERABYTES

PHOTOS UPLOADED TO FACEBOOK EACH MONTH

THE PETA AGE

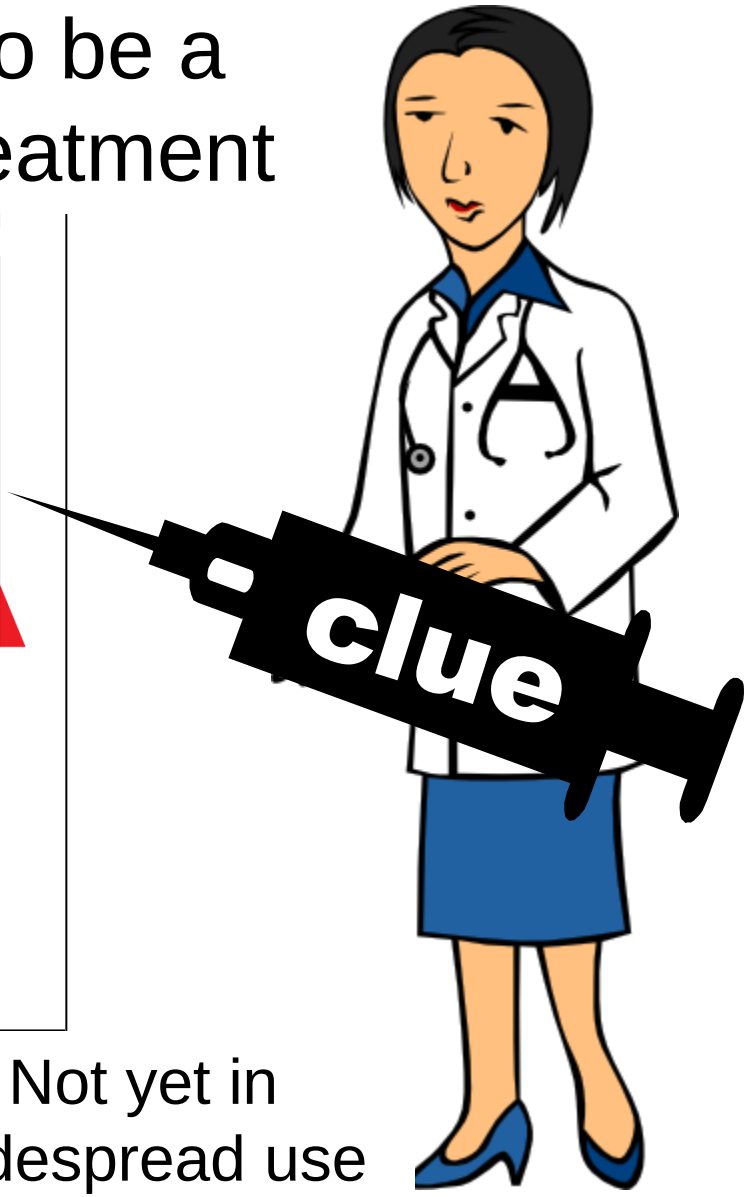
460 TERABYTES

ALL THE DIGITAL WEATHER DATA COMPILED BY THE NATIONAL CLIMATIC DATA CENTER

530 TERABYTES

ALL THE VIDEOS ON YOUTUBE

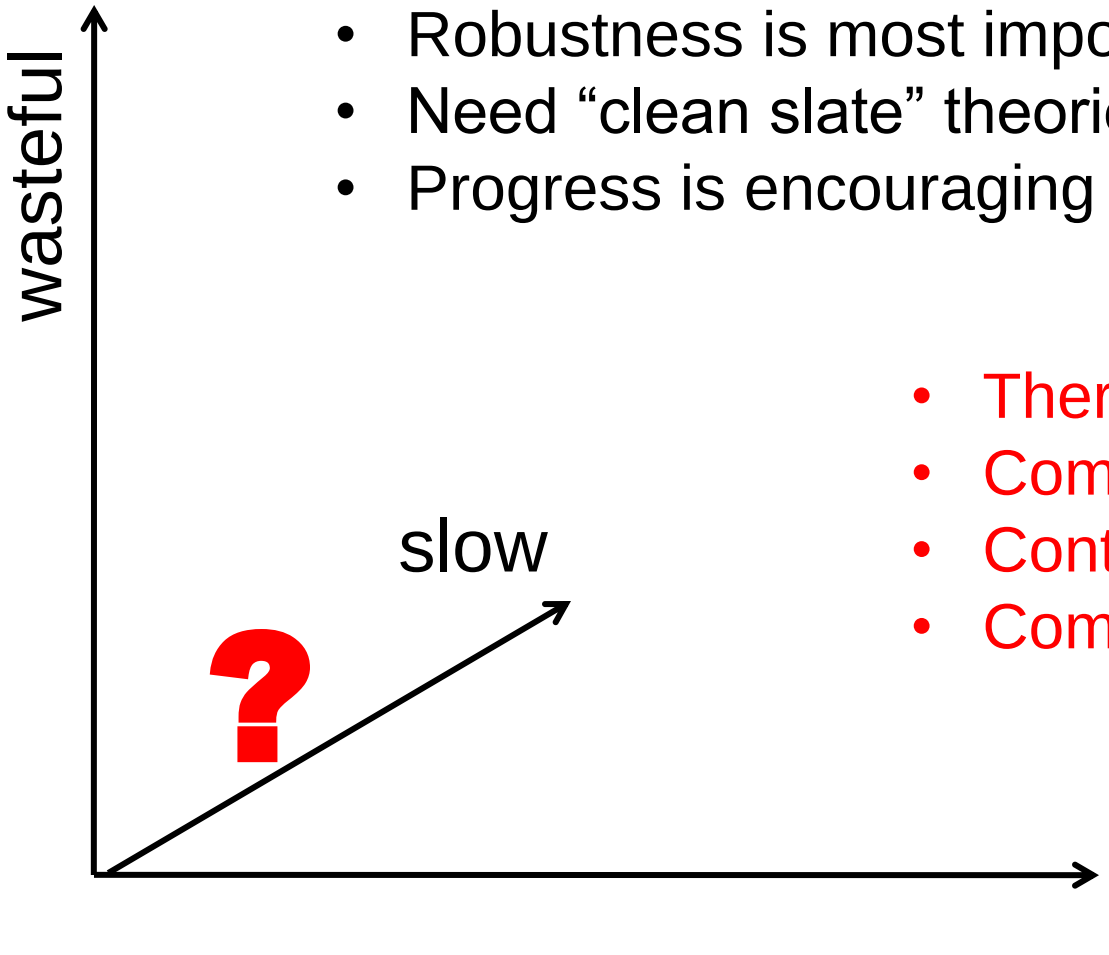
Fortunately there seems to be a treatment



Not yet in widespread use

Standard theories are severely limited

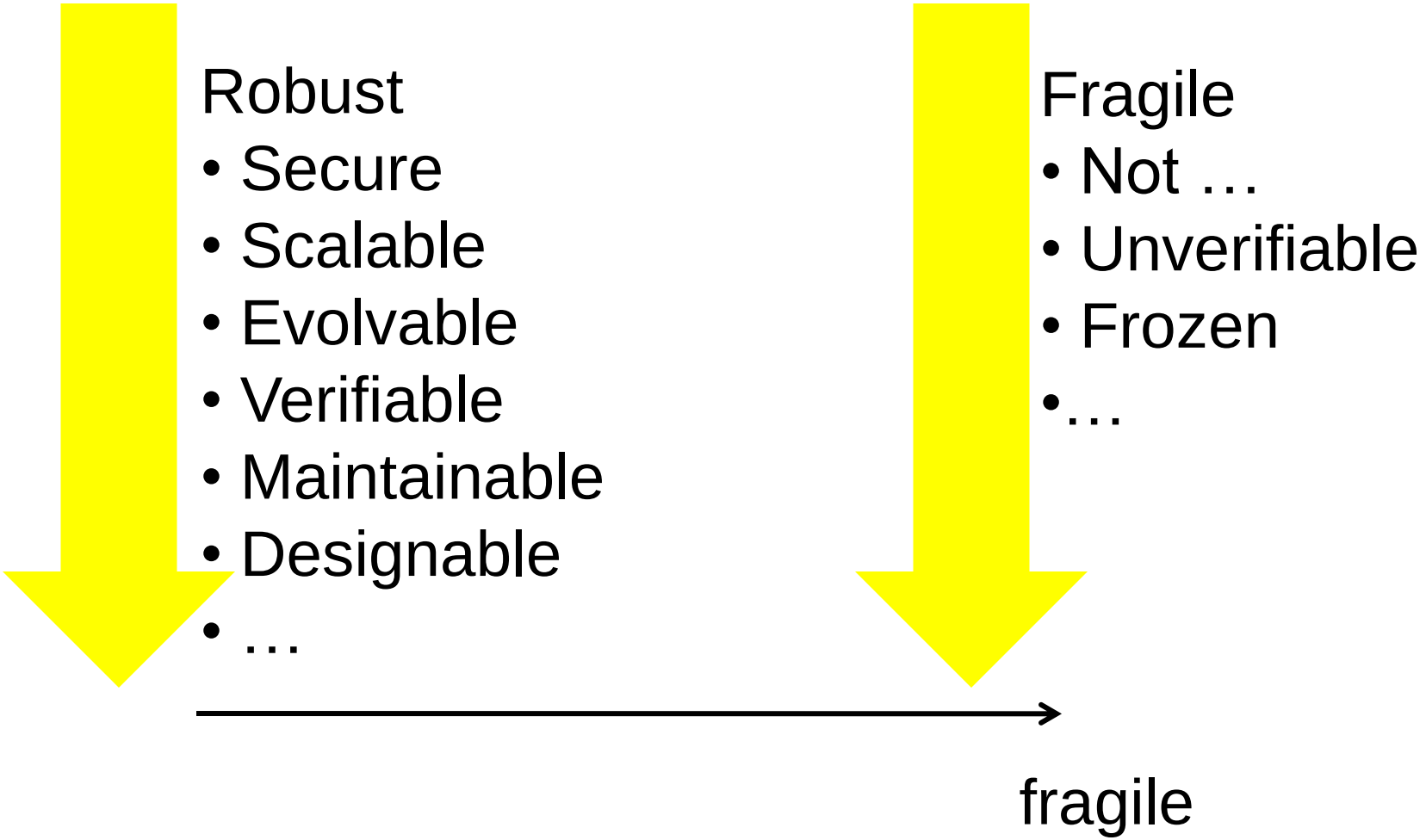
- Each focuses on few dimensions
- Important tradeoffs are ***across*** these dimensions
- Speed vs efficiency vs robustness vs …
- Robustness is most important for complexity
- Need “clean slate” theories
- Progress is encouraging



- Thermodynamics (Carnot)
- Communications (Shannon)
- Control (Bode)
- Computation (Turing)

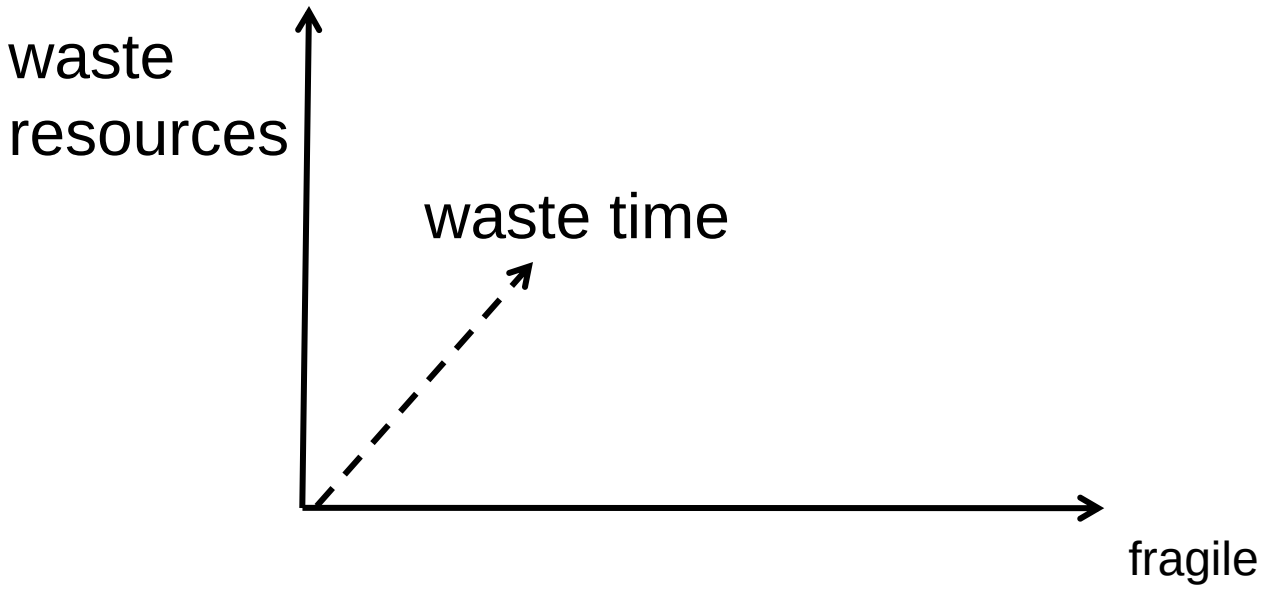
Most dimensions are robustness

Collapse for visualization

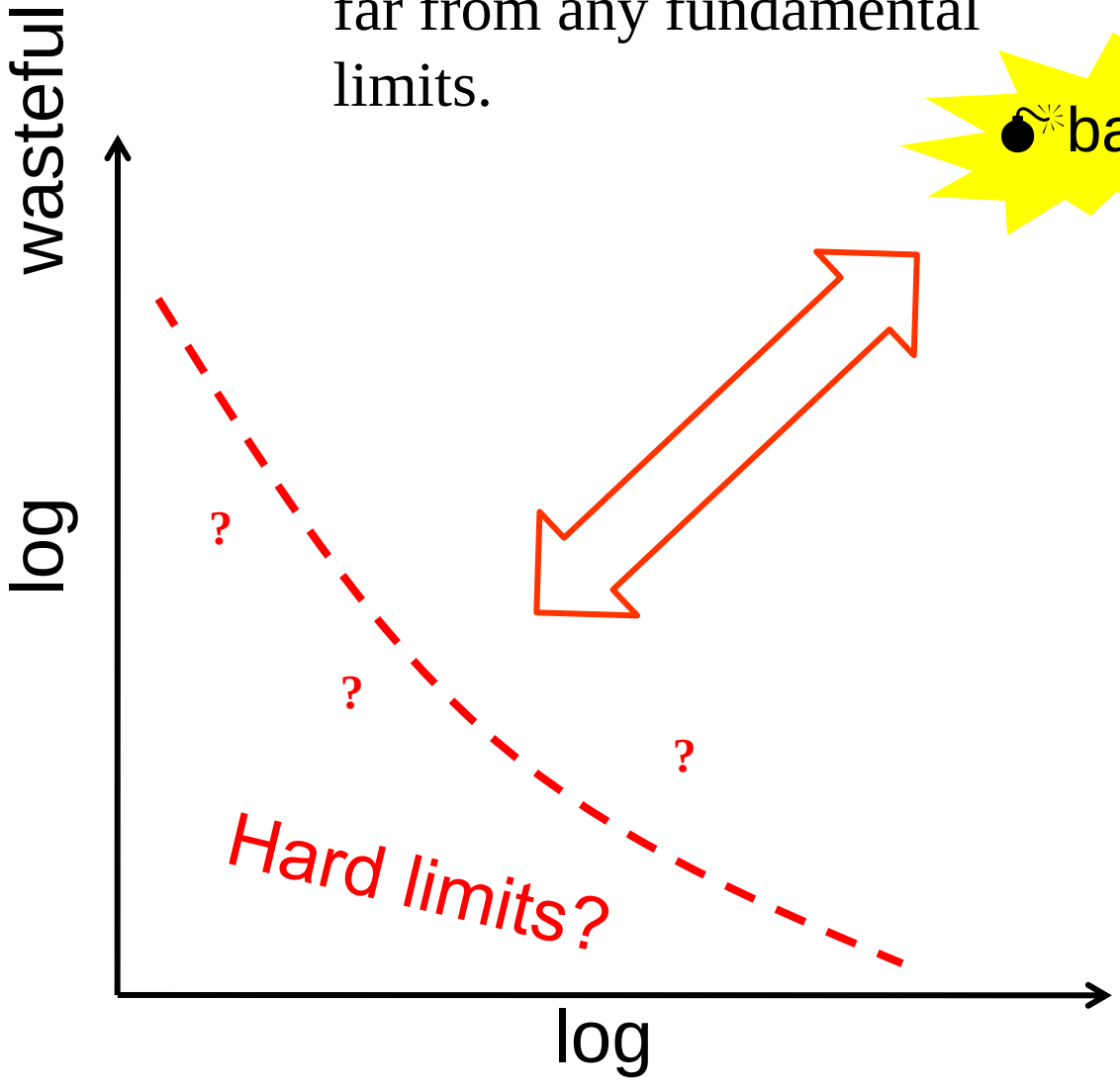


- Important tradeoffs are ***across*** these dimensions
- Speed vs efficiency vs robustness vs …
- Robustness is most important for complexity
- Collapse efficiency dimensions

wasteful



But many existing systems and architectures are clearly far from any fundamental limits.



So fixing "bugs" in existing architectures has most immediate impact.

Note: "log" suggests orders of magnitude variations

What do we want from our systems/architectures?

- Efficient use of resources (sustainability)
  - Small consumed environmental resources and produced waste
  - Inexpensive components, small capital investment
  - Efficient processes: Design, manufacture, maintain, manage
- Robustness to perturbations
  - Reject external disturbance and suppress internal noise
  - Tolerate component failures and uncertainty
  - Secure against malicious attack and hijacking
  - Scalable to large system size
  - Evolvable on long time scales to large changes
  - Human actors have aligned incentives
- Predictable, Verifiable, Understandable
  - Limit unintended consequences
  - Experiments and data that are easily reproducible
  - Models (simple and analyzable), elegant theorems, short proofs
  - Experience that is reliable guide to the future

There are hard tradeoffs (laws) among/between these

Complexity in reality

- Illustrative examples can be bewildering
  - requires daunting domain details
  - dominated by (poorly understood) robustness tradeoffs ***not*** (more easily understood) minimal functionality
- Profound error/confusion
  - ***within*** mainstream science
  - even more confusion at policy level
- Lack of shared epistemologies
  - Even the most basic elements of discourse are in dispute
  - Nature of evidence, proof, statistics, valid argument,…
  - What is meant by “complexity, nonlinearity,…”

Case studies in efficiency, robustness, complexity

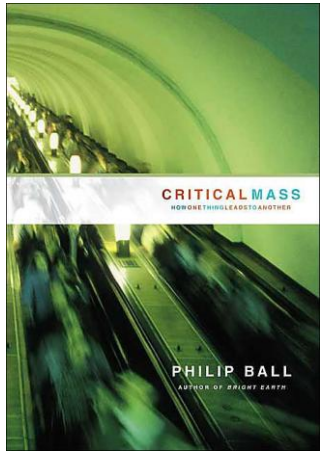
- Physiology/architecture/evolution
  - Bacteria
  - Human
  - Ecosystem
- Network architecture/evolution
  - Internet (comms and computing), cyberphys
  - Power, transportation, water, waste, etc…
  - Manufacturing, supply chain, …
  - Markets, finance, economics,…
  - Politics, sociology, religion, …
- “Toy” examples: Lego, fashion, games, art, literature,…
- Many popular toy models are (unfortunately) misleading
- Multiscale physics (stat mech, fluids, QM, …)

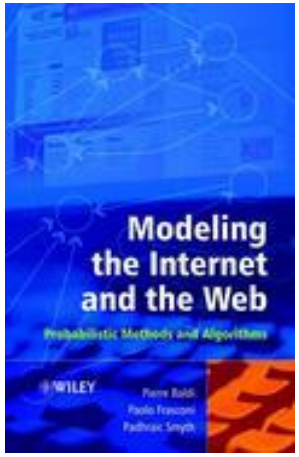
(Not) Shared Epistemologies

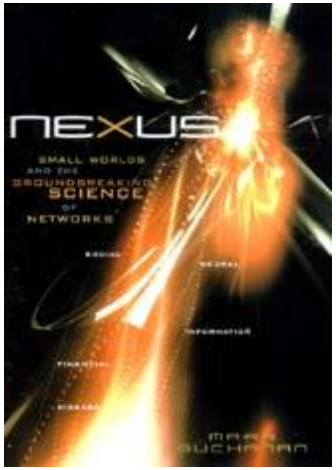
- Policy/politics
  - No consistent or coherent view of evidence, proof, etc
  - Ideologies/agendas (not surprising, but) frustrating
- Science (i.e. physics) of “complexity”
  - Dominates S&T input to policy and politics
  - Internally coherent, but shockingly political, ideological
  - But inconsistent with…
- Math, engineering, medicine and complexity
  - Surprisingly consistent epistemology
  - Yet fragmented and incoherent in details
  - No common language or coherent voice
  - Lose to ideologues with clear agendas

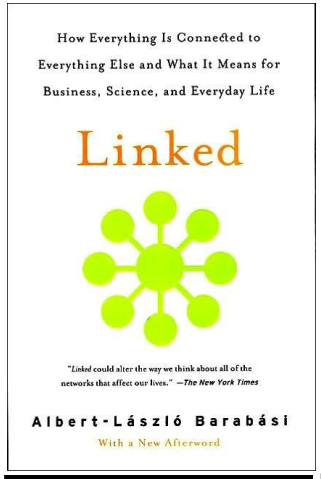
What we need to connect

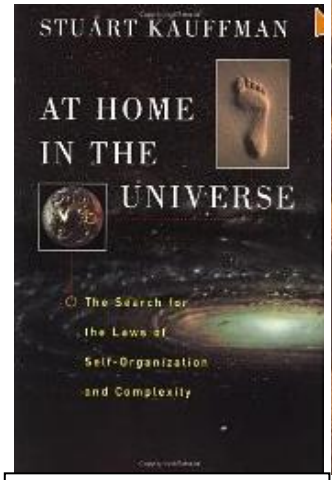
- More integrated mathematics
- Real complex networks (Internet, smartgrid,…)
  - Function and structure
  - Architecture and control
- ~~"New sciences?"~~ (Complexity, networks,)
  - ~~Creation science and intelligent design~~
  - ~~Edge of chaos~~
  - ~~Self-organized criticality~~
  - ~~Scale-free~~
  - ~~…~~

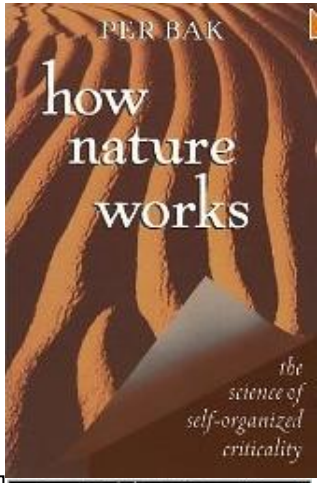

CRITICAL MASS
HOW ONE THING LEADS TO ANOTHER
PHILIP BALL
AUTHOR OF BRIGHT EARTH

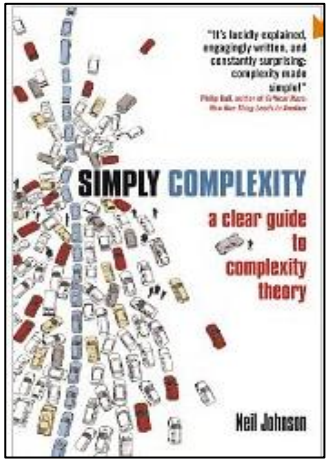

Modeling the Internet and the Web
Probabilistic Methods and Algorithms
WILEY
Pierre Baldi
Paolo Frasconi
Padhraic Smyth

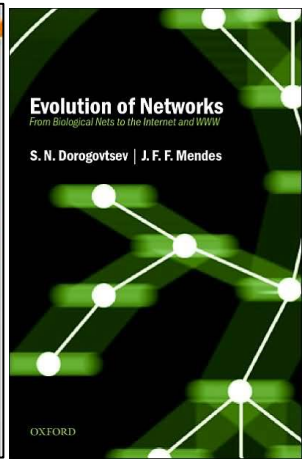

NEXUS
SMALL WORLDS AND THE GROUNDBREAKING SCIENCE OF NETWORKS
MARK BUCHANAN

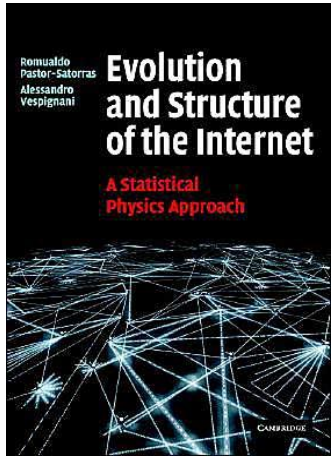

How Everything Is Connected to Everything Else and What It Means for Business, Science, and Everyday Life
Linked
"Linked could alter the way we think about all of the networks that affect our lives." —The New York Times
Albert-László Barabási
With a New Afterword

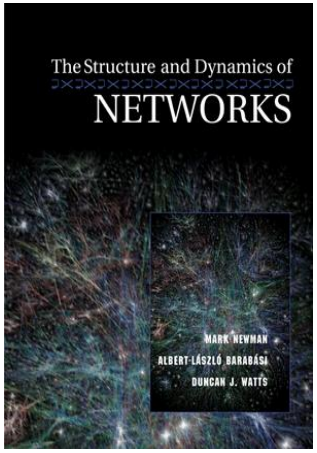

STUART KAUFFMAN
AT HOME IN THE UNIVERSE
The Search for the Laws of Self-Organization and Complexity

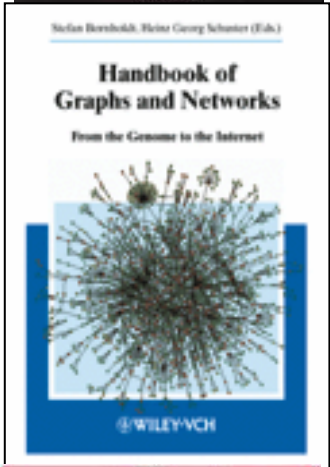

PER BAK
how nature works
the science of self-organized criticality

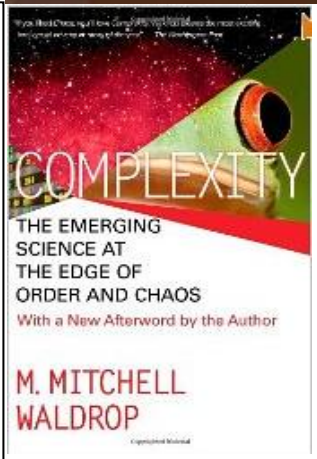

"It's lucidly explained, engagingly written, and constantly surprising: complexity made simple!"
SIMPLY COMPLEXITY
a clear guide to complexity theory
Neil Johnson

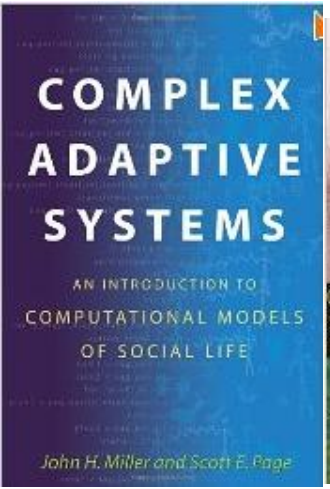

Evolution of Networks
From Biological Nets to the Internet and WWW
S. N. Dorogovtsev | J. F. F. Mendes
OXFORD

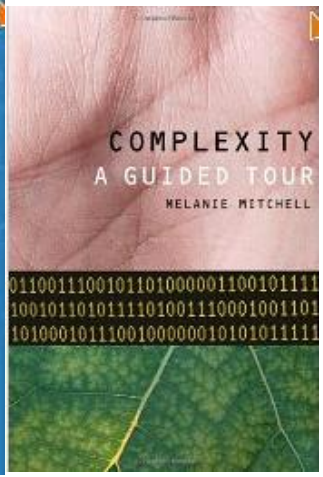

Romualdo Pastor-Satorras
Alessandro Vespignani
Evolution and Structure of the Internet
A Statistical Physics Approach
CAMBRIDGE

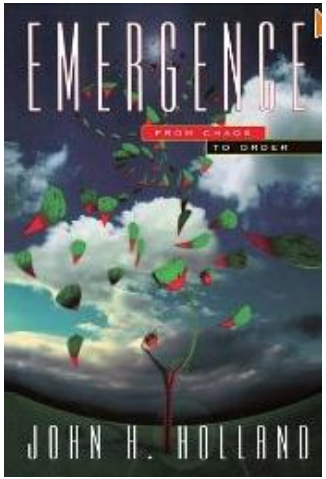

The Structure and Dynamics of NETWORKS
MARK NEWMAN
ALBERT-LÁSZLÓ BARABÁSI
DUNCAN J. WATTS

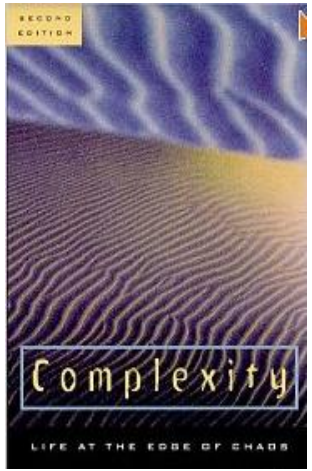

Handbook of Graphs and Networks
From the Genome to the Internet
WILEY-VCH

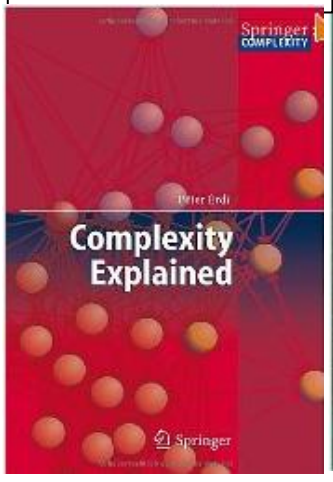

COMPLEXITY
THE EMERGING SCIENCE AT THE EDGE OF ORDER AND CHAOS
With a New Afterword by the Author
M. MITCHELL WALDROP

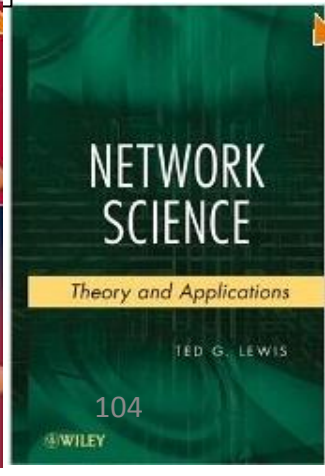

COMPLEX ADAPTIVE SYSTEMS
AN INTRODUCTION TO COMPUTATIONAL MODELS OF SOCIAL LIFE
John H. Miller and Scott E. Page


COMPLEXITY
A GUIDED TOUR
MELANIE MITCHELL


EMERGENCE
FROM CHAOS TO ORDER
JOHN H. HOLLAND


SECOND EDITION
Complexity
LIFE AT THE EDGE OF CHAOS


Springer COMPLEXITY
Peter Erdi
Complexity Explained
Springer


NETWORK SCIENCE
Theory and Applications
TED G. LEWIS
WILEY

Complex systems?

Even small amounts can create bewildering complexity

Fragile

- Scale
- Dynamics
- Nonlinearity
- Nonequlibrium
- Open
- Feedback
- Adaptation
- Intractability
- Emergence
- …

Complex systems?

Robust

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Fragile

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Complex systems?

Robust complexity

- Scale
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- …

- Resources
- Controlled
- Organized
- Structured
- Extreme
- Architected
- …

Architecture

Robust complexity

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- …

New words

Emergulent

Emergulence at the edge of chaocritiplexity

Fragile complexity

- Scale
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- Nonequlibrium
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- Emergence
- …

Danger: bad scholarship ahead

- Huge literatures going back a century (at least)
  - That I don't know all that well (not my main research)
  - Bewildering amount of domain details
  - Persistent mysteries (and controversy)
  - Exist consistent, coherent components of the story
  - Even experts know only small fraction
- Large teams of collaborators (i.e. the real talent)
- Very "new" results
  - Not "written up" yet, just the slides you see (sort of)
  - Intended to be universal/accessible (but aren't yet)
  - Illustrate principles beyond the domains
  - Pedagogy, not depth

Universals in complex, robust networks

Today's focus on fundamentals

- Concepts: Complexity, robustness, and fragility
- Theory: Fundamental laws, constraints, tradeoffs
- Network architecture
- Illustrate with "simple" and familiar case studies

- Warm up with some (hopefully familiar) example